Canadian Space Exploration

Science and Space Health Priorities for Next Decade and Beyond

A Community Report from the 2016 Canadian Space Exploration Workshop and Topical Teams

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Executive Summary

On 24-25th November 2016, 208 scientists, engineers and students associated with Canadian universities, industry and government gathered in Montreal to consider Canada's future in space under the Space Exploration theme '*Science and Space Health Priorities for the Next Decade and Beyond*'.

This consultation event was co-ordinated by the Canadian Space Agency (CSA) in the context of the Government of Canada's Innovation Agenda, and focussed on space exploration as an engine for innovation and a source for youth Science, Technology, Engineering and Mathematics (STEM) inspiration. This event highlighted science opportunities and advances in a number of technology fields such as optics, robotics, sensors and data, with potential for new application developments in various sectors including health.

Workshop participants welcomed this event with much enthusiasm, as they recognised that a renewal of science priorities by the space exploration science community was well-timed to position Canada for future space exploration opportunities and to enable socio-economic growth.

Sustaining Canadian Science Leadership and Excellence

Canada has a legacy of excellence in space. For example, Canada's normalised citation index for astronomy and astrophysics positions Canada as the leader in the Group of 7 (G7) in this field. As a result of strengths in many space sciences, Canada is often sought after for science and engineering contributions to international Space Exploration missions in space astronomy, planetary science and space health.

The previous meeting of the space exploration science community was held in December 2008, when Canada's unique advantages for leading several promising areas of research were proudly described in the resulting community report 'Canadian Science Priorities for the Global Exploration Roadmap', the predecessor to this current report. At that time, NASA's Mars Phoenix Lander mission had just been completed, and carried the maple leaf to the surface of Mars in the form of a Canadian weather station which was the first laser-based instrument from any nation to operate from the surface of another planet. Canada had also become a partner in the James Webb Space Telescope (JWST), a top priority of the Canadian Astronomical Society's (CASCA) Long Range Plan (LRP), and was developing its largest-ever and most challenging space science contribution. In addition, Canadian community-driven microgravity research investigations, including some related to space health, were being considered for the full utilisation phase of the International Space Station (ISS).

Since 2008, financial constraints have seen less funding directed at fundamental science and space which has seen several prominent international projects move forward without Canada's participation. This has raised concerns about the sustainability of the community that have been reflected in several community white papers and the 2017 Fundamental Science Review.

Science to Inspire the Next Generation of Canadians

Today, the pace of change is accelerating, and Canada stands at a defining moment in a global innovation race, where non-traditional space-faring nations are launching new space science programs as flagship innovation and STEM initiatives. For example, the United Arab Emirates (UAE) has recently approved its first mission to Mars, named Hope.

In the spirit of the Government of Canada's Innovation and Skills Plan, Space Exploration drives a culture of innovation that reaches into Canadian schools as one of the most powerful sources of inspiration for STEM. Space Exploration captures the imagination of the very young, and the ambition, optimism and creativity of youth. It is accessible to all, in the expanses of our night sky and the sense that outer space transcends humanity, embracing our diversity.

Space Exploration offers three profound knowledge frontiers: a cosmic frontier of galaxies and stars, where we can probe how the Universe came to be the way we observe it today; a solar system frontier of neighbouring planets, moons, asteroids and comets as challenging targets for robotic and scientific exploration; and, a human exploration frontier, where limits of human endurance are both challenged and explored, and where humankind is looking to expand a zone of economic development beyond Low Earth Orbit (LEO). The search for life beyond Earth is one of the most compelling scientific and societal goals.

A nation contemplating such frontiers, seeks to design the future, and in doing so, creates the inspiration to push its next generation of scientists and engineers to reach further into space while generating socio-economic opportunities here on Earth.

Canadian Space Agency Context

The Space Exploration sciences are 'Big Science', requiring the infrastructure of space missions or human spaceflight for implementation, and careful consideration of opportunities to ensure maximum value for investments. For astronomy, access to space produces measurements that are not possible from Earth due to interference or blocking from the Earth's atmosphere. For planetary science, the steps of orbiting, then landing on a solar system body, then bringing a sample back, each bring a dramatic increase in knowledge. For space health, the space environment presents physiological changes similar to aging, as well as an extreme environment for remote medicine relevant to delivery of health care in isolated Arctic communities. Industry advances in Space Exploration signature technologies, especially optics and robotics, are critical to enable steps forward, and create jobs and prosperity through technological innovation.

Concerning space astronomy and planetary science, which are considered fundamental sciences by the CSA, the Canadian academic communities are recognised as the primary stakeholders, with future Canadian contributions intended to be science-driven and technology-enabled.

For space health, the CSA program mandate is to mitigate health risks for future astronaut flights. The community priorities identified in this report are an important input that allows the CSA to best prioritise investments in space health in areas of Canadian strength and with shared benefits to health research of an aging and increasingly sedentary Canadian population.

At present, the Space Exploration sciences are supported by the CSA with some foundational research funded by the granting councils. The existence of end-to-end roadmaps as presented in this report can allow for the kind of sustained, co-ordinated, career-following, government investment recommended by the Fundamental Science Review.

Purpose of this Report

This report reflects discussions at the 2016 Canadian Space Exploration Workshop (CSEW) where Canadian scientific and industrial experts presented ideas for consideration as priorities of Canada's Space Program. These discussions and ideas were further developed by the following eight Topical Teams (TT):

- Astrobiology;
- Planetary Atmospheres;
- Planetary Geology, Geophysics and Prospecting;
- Planetary Space Environment;
- High Energy Astrophysics;
- Cosmology;
- Cosmic Origins; and,
- Space Health.

Each TT was university-led, including industry and student representation, with a mandate to produce a specific chapter of this report.

As a result, the content of this report reflects the views of the communities as understood by the TT authors.

This report provides a compelling vision for a renewed Canadian Space Exploration program. It provides ample evidence of a community prepared to maximise the impact of Government investments in space.

The Science Priorities

After a nearly two year long process, the community has selected a number of priorities for each of the eight space exploration Topics, with roadmaps for associated foundational research, instrument, technology and/or mission investments, and mission data analysis, that are designed to span one or more decades.

The report addresses priorities for missions that will launch in the ‘Next decade and beyond’. This long planning horizon is necessary for space astronomy and planetary science missions. It is generally too late in 2017 to add new contributions to mid- or large-class space missions planned to launch before 2022. For space health, the mid-2020’s also mark the beginning of an expected transition to extend human exploration capabilities at the ISS to new infrastructure in deep space.

TTs were asked to prioritise their science objectives and investigations based on the sum of three criteria:

- Science Merit,
- Importance to Community, and
- Benefits to Canada.

The task of community prioritisation was challenging and a balance approach was taken between enabling an individual’s ground-breaking idea, and providing a framework that allows intelligent program level resource management and capacity building. This balance will be enabled by regular updates to the report, which should occur at a minimum every 5 years.

For astronomy, the CASCA LRP provides rigorous prioritisation of opportunities often focussing on flagship missions. The task provided to astronomy TTs was intended to be complementary, providing an expanded roadmap that included foundational research and consideration of smaller missions.

It should be noted that the Planetary Science TTs declined to prioritise solar system destinations, favouring instead a future open competitive selection process for planetary mission contributions.

The ‘Summary of Priorities’ tables below are structured by Discipline and by TT:

- Table 1 Summary of Space Astronomy Priorities
- Table 2 Summary of Planetary Science Priorities
- Table 3 Summary of Space Health Priorities

For each TT, the Objectives are in priority order, unless otherwise stated.

Table 1 Summary of Space Astronomy Priorities

2017 Canadian Space Exploration
Science and Space Health Priorities for Next Decade and Beyond
Summary of Space Astronomy Priorities

Space Astronomy: *Modern astronomy offers answers to fundamental questions about our universe and our place in it. Astronomy is the study of the physics of the universe and encompasses a wide range of subjects from the birth of the universe, its composition and evolution to the formation of planets, stars and galaxies.*

Astronomical research covers vast areas of specializations and some can only be conducted from space, but for the purpose of grouping the research priorities here, they will be categorized into three areas:

***Cosmology**: Where did all the matter come from, can we explain the very early stages of the universe and how it expanded?*

***Cosmic Origins**: How did stars and galaxies form and evolve to what we see today? How did our solar system and exoplanets form? Are there signs of life elsewhere? Are we alone?*

***High Energy Astrophysics:** Most of light-emitting matter in the universe shines in x-rays. How do we understand the nature of matter in extreme temperatures, gravity and magnetic fields?*

Astronomy objectives are not in priority order.

Cosmology TT: 23 members from 11 organisations	COS-01 - Cosmic Microwave Background: Probing the Physics of Inflation – the Big Bang theory
	COS-02 - Dark Energy – seeking to understand why the universe is expanding and accelerating
	COS-03 - The Nature of Dark Matter – which has gravitational effects on galaxies but it is not visible
	COS-04 - The End of the Cosmic Dark Ages – when the first stars and galaxies formed
Cosmic Origins TT: 32 members from 14 organisations	COR-01 - Origins in The Ultraviolet: A Treasure Trove of Astrophysics: young, hot stars; hot intergalactic medium. Photometric red-shift for weak lensing (clues to dark energy)
	COR-02 - Exoplanet detection via gravitational microlensing, and spectroscopy of exoplanet atmospheres
	COR-03 - Survey of earliest galaxies (high redshift Universe)
	COR-04 - Explore the hidden universe obscured by dust – far infra-red space telescopes can see through the dust and reveal star and solar system formation
	COR-05 - Direct imaging of nearby Earth-like exoplanets for biosignatures
High Energy Astrophysics TT: 30 members from 17 organisations	HEA-01 - Accretion physics in the inner regions of compact objects – matter falling onto neutron stars and black holes emit X-rays
	HEA-02 - Feedback Mechanisms on all Scales – black holes can create jets of matter in a galaxy; supernova can create heavy elements that become material for next generation stars and planets
	HEA-03 - Demographics of Black Holes – almost every galaxy has a super massive black hole at its center. How did they come about and influence the evolution of its host?
	HEA-04 - Physics of dense matter and extreme magnetic fields – extreme conditions that cannot be replicated on Earth – contributes to knowledge in fundamental physics

Table 2 Summary of Planetary Science Priorities

2017 Canadian Space Exploration ***Science and Space Health Priorities for Next Decade and Beyond*** **Summary of Planetary Science Priorities**	
Planetary Science: *Planetary exploration involves investigating the characteristics of planets and planetary bodies (e.g., moons, asteroids and comets) in our Solar System, including the geological record preserved from their surfaces, samples, and interiors; the composition and evolution of their atmospheres; the interaction of their surfaces, magnetic fields and atmospheres with the solar wind. From these characteristics we can infer which environments in the Solar System may have been, or are presently suitable for life.* *For the purpose of this report, planetary science priorities are categorised into four Topics:* *The goal of astrobiology is to answer the fundamental question: Does life exist elsewhere, other than Earth?* *The composition and chemistry of gaseous components, aerosols, and dust in planetary atmospheres provide a record of the evolution of the atmosphere over time, its interaction with the planetary surface, and with the planetary space environment.* *While* ***planetary geology, geophysics, and prospecting*** *encompasses a range of investigations – mostly relating to the geological record of solid planetary bodies in the Solar System, as Canada is a world leader in mining and mineral exploration, the synergy between terrestrial activities and near-future extraterrestrial resource exploration leads to a significant potential for Canada to be actively involved in these types of activities.* *The harsh, radiation-rich environments present in near-planetary space is the result of interaction between the Sun and the planets and other bodies in the Solar System; an understanding of* ***planetary space environments*** *is a necessary prerequisite to enable planetary exploration.*	
Astrobiology TT: 21 members from 11 organisations	AB-01 Biosignature Characterisation -understanding the target signs of life (biosignatures)
	AB-02 Biosignature Detection - developing the instruments that can detect signs of life
	AB-03 Accessing the Subsurface for Astrobiology - below the harsh surface radiation environment of Mars, Europa and other astrobiology targets
	AB-04 Accessing Special Regions - areas of Mars where temperature and availability of liquid water are believed most favourable for life
	AB-05 Exoplanets: Characterization and Detection of Biosignatures - remote sensing that can be applied to the search for life beyond our solar system.
Planetary Atmospheres TT: 19 members from 11 organisations	PAT-01 Understand Mars Surface-Atmosphere Interactions -the present-day cycle of water on Mars
	PAT-02 Understand the Chemistry of Planetary Atmospheres - the composition of atmospheres and trace gases that can indicate life or geological activity
	PAT-03 Constrain the Dynamics of Planetary Atmospheres - winds and weather
	PAT-04 Understand Atmospheric and Exospheric Aerosols - dust in climate and storms
Planetary Geology, Geophysics and Prospecting TT: 33 members from 17 organisations	PGGP-01 Document the geological record and processes that have shaped the surface of the terrestrial planets, their moons, icy satellites and asteroids
	PGGP-02 Determine the Resource Potential of the Moon Mars and Asteroids
	PGGP-03 Understand the origin and distribution of volatiles on the terrestrial planets and their moons asteroids and comets
	PGGP-04 Determine the interior structure and properties of the terrestrial planets and their moons, icy satellites and asteroids
	PGGP-05 Understand the impact, threat and hazards posed by impact events on the Earth and other solar system bodies
	PGGP-06 Understand surface modification processes on airless bodies.
Planetary Space Environment TT: 10 members from 6 organisations	PSE-01 To understand the role of magnetic fields, plasma and atmosphere-ionosphere dynamics on the history and evolution of planets and other solar-system bodies
	PSE-02 To understand and characterize the plasma processes that shape the heliosphere and drive planetary and interplanetary space weather and related effects which create hazards to space exploration

Table 3 Summary of Space Health Priorities

<table>
<tr><th colspan="2">2017 Canadian Space Exploration
Science and Space Health Priorities for Next Decade and Beyond
Summary of Space Health Priorities</th></tr>
<tr><td colspan="2">**Space Health**: *Canada is one of five partners on the International Space Station, one of the world's most remarkable engineering and political achievements. Canada's iconic contribution of the robotic arms (Canadarm2 + Dextre) on the ISS has provided the direct benefits of an allocation of missions for Canada's astronaut core and use of the station for Canadian microgravity research.*

Today, the duration of astronaut missions on the International Space Station are regularly as long as 6 months. Space Health research to date indicates significant impacts on human physiology and health due to microgravity including bone loss and circulatory issues, some of which have symptoms common to aging.

As humankind explores beyond low Earth orbit to the Moon and Mars, astronaut mission durations will extend. In addition to microgravity, astronauts will experience increased radiation environments beyond the van Allen belts that protect Earth, and increased isolation and risk, the further from our home planet they are, requiring the need for new space medicine and remote healthcare.

The Space Health Topical Team has reviewed the current state of our understanding of space health issues from the molecular and genetic levels to spacecraft health care systems and Earth-based analogue facilities. From that review future directions were identified and priorities quantified on the basis of Scientific Merit and Benefits to Canadians where we considered both the research community and the larger Canadian society, especially for health care, when we considered Benefits. The review and prioritization of Canadian space health research was organized under four Objectives.</td></tr>
<tr><td rowspan="4">**Space Health TT**:
30 members from 18 organisations</td><td>SH-01: To better understand the risks to living organisms of radiation exposure beyond low-Earth orbit and develop effective countermeasures</td></tr>
<tr><td>SH-02: To better understand biological and physiological changes that occur in reduced gravity environments and to develop effective countermeasures</td></tr>
<tr><td>SH-03: To develop a more integrated understanding of the biological and physiological effects of the space environment and develop integrated countermeasures</td></tr>
<tr><td>SH-04: To better understand the psychological effect of spaceflight and develop effective countermeasures</td></tr>
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1 Forward by the CSA Space Exploration Planning Group

1.1 Motivation: The Need for Community Priorities

The Space Exploration sciences are ‘Big Science’, requiring the infrastructure of space missions or human spaceflight for implementation, and careful consideration of opportunities to ensure maximum value for investments. For astronomy, access to space produces measurements that are not possible from Earth due to interference with the Earth’s atmosphere. For planetary science the steps of orbiting, then landing on a solar system body, then bringing a sample back, each bring a dramatic increase in knowledge. For space health, the space environment presents physiological changes similar to aging, as well as an extreme environment for remote medicine relevant to delivery of health care in isolated arctic communities. Industry advances in Space Exploration signature technologies, especially optics and robotics, are critical to enable steps forward, and create jobs and prosperity through technological innovation.

The goal of the Canadian Space Exploration Strategic Planning function is to plan and coordinate Canadian space exploration activities and to maintain the key space capabilities of the Canadian space exploration sector and addresses the scientific needs of the Canadian space exploration community. To meet these needs, activities are carried out aiming at identifying and supporting scientific, technological, and operational solutions, thereby preparing and positioning Canada for future space exploration missions. The organisation of the Canadian Space Exploration Workshop (CSEW) and Topical Teams (TT) consultation to update science priorities is a key activity of Strategic Planning.

Space Exploration Preparatory Activities form an integral and critical part of the Canadian Space Agency’s (CSA) exploration strategic planning activities. They define the science investigations as well as the science and technology developments most likely to be required in future space exploration missions of interest to Canada, and assesses potential contributions that Canada could make to such missions.

The outputs of these activities inform the decision process when selecting contributions to international space exploration missions by providing goals, requirements, assessments of current technology maturity as well as cost, risk and timelines to achieve said goals.

The CSA undertakes relevant preparatory activities in close collaboration with industry, academia and foreign space agencies (e.g. through the International Space Exploration Co-ordination Group) to be in the position to provide its contributions to future space exploration missions.

For space astronomy and planetary science, which are considered fundamental sciences by the CSA, the Canadian academic community are recognised as the primary stakeholders, with future contributions to missions intended to be science-driven, technology-enabled, and Space Exploration Preparatory Activities are anticipated to respond directly to priorities in this report.

For space health, the CSA program mandate is to mitigate health risks for future astronaut flights. The community priorities identified in this report are an important input that allows the CSA to best prioritise investments in space health in areas of Canadian strength and with shared benefits to health research of an aging Canadian population.

The long-term investment strategy is informed by regular conversations with CSA Space Exploration Consultation Committees.

The Space Exploration sciences are also supported to differing degrees by Canada’s granting councils.

This report was designed to produce end-to-end roadmaps that could facilitate the kind of sustained, co-ordinated, career-following government investment recommended by the Fundamental Science Review.

This report compiles the eight TT reports, grouped by discipline (Planetary Exploration, Space Astronomy, and Space Health).

The report reflects the views of the communities as understood by the TT authors.

1.2 The Canadian Space Exploration Workshop Event

The CSEW was held at the Marriott Montreal Chateau Champlain on November 24-25th 2016 as a consultation within the framework of the Government of Canada's Innovation Agenda on the theme 'Space Exploration: science and space health research priorities for missions in the next decade' and beyond.

The workshop objectives were supportive of near term mission priorities but fundamentally looking at a longer term horizon to better inform future decision-making and to take full advantage of risk reduction preparatory investments pre-mission selection.

The workshop over the 2 days included 6 parallel breakout sessions:

(1) Space Astronomy;

(2) Space Health;

(3) Astrobiology;

(4) Planetary Atmospheres;

(5) Planetary Space Environment;

(6) Planetary Geology, Geophysics and Prospecting.

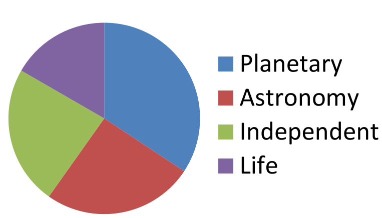
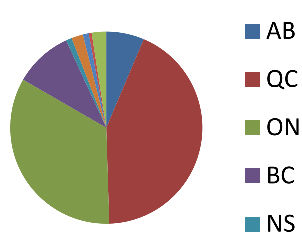
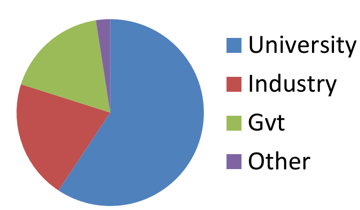
There were high levels of participation and enthusiasm from industry and academia (208 attendees, statistics Table 1-1); including significant student and Postdoctoral Fellow (PDF) participation: three poster prizes awarded based on merit, visual and oral presentation. At the end, the community remarked that the CSEW process is an important consultation, and should repeat at least every 5 years.

There were 208 participants from across Canada (and some US), compared with the original target of 150. A compilation of Abstracts is available here:

ftp://ftp.asc-csa.gc.ca/users/ExP/pub/Publications/CSEW2016/Abstracts-Resumes/CSEW_2016_Abstracts%20Compilation.pdf.

Table 1-1 Participation Statistics

Discipline	No. of Participants	No. of Abstracts	No. of Posters
Space Astronomy	52	16	10
Planetary Exploration	70	33	17
Life Science	34	5	4
Other (technology)	47		
CSA	5	1	5

Participation by Discipline	Participation by Province	Participation by Organization
		

1.2.1 Immediate Workshop Outcomes

Canadian academic, industry and space health communities are re-engaged and keen to work with CSA to advance space astronomy, planetary exploration and space health objectives of the Canadian Space Program to meet Government innovation goals and priorities.

The CSEW demonstrated to the community an open, public entry point for their ideas related to planetary and space astronomy missions and space health, and the first step in a CSA-co-ordinated prioritisation process designed to address increasing numbers of unsolicited proposals. Unsolicited proposals from the community for mission opportunities are difficult for the government to respond to.

1.2.2 Workshop Recommendations

The workshop concluded that Government needs to respond to community engagement with opportunities to advance community priorities through Space Exploration Preparatory activities in Fiscal Year (FY) 17-19 and address the longer term community need for an “ambitious, sustainable, predictable, balanced program” for space astronomy and planetary exploration, echoed from recent Aerospace Industries Association of Canada (AIAC) recommendations for regular small mission opportunities.

- Nominally funded in SE Preparatory Activities FY 17-19 (science maturation, concept studies)
- Space Exploration grants program (Science Definition, Participating Scientists/Mission Co-Investigators/Guest Observers)

1.3 Topical Teams

In 2015, CSA competitively selected TTs to identify scientific objectives and priorities for investigations and related activities in the Space Exploration disciplines as listed below. Priorities were to be relevant to opportunities and missions with target launch dates in the mid-2020s or beyond.

The members of the TTs were selected for their expertise and commitment to contribute to the consultations; members were mostly from universities (including post-doctoral fellows and students) and some from industry.

The resulting eight TTs are:

- Planetary Exploration - Astrobiology (solar systems and exoplanets)
- Planetary Exploration - Planetary Atmospheres
- Planetary Exploration - Planetary Geology; Geophysics and Prospecting
- Planetary Exploration - Planetary Space Environment
- Space Astronomy - Cosmology (Cosmic Microwave Background (CMB), dark energy)
- Space Astronomy – Cosmic Origins (galaxies, stars, exoplanets)
- Space Astronomy - High Energy Astrophysics (HEA)
- Space Health

Each TT was managed by a Chairperson who was contracted to prepare and submit a report that encapsulated the results of consultations and discussions within their team. They were also tasked to identify discipline specific opportunities, priorities and the steps needed to incorporate these in space missions for the next decade and beyond.

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2 Space Astronomy in Canada Overview

Chair Name	Topical Team	Affiliation
Roberto Abraham	"Origins"	University of Toronto
Luigi Gallo	"High Energy Astrophysics"	St-Mary's University
Douglas Scott	"Cosmology"	University of British Columbia

Astronomy seeks answers to some of the deepest questions that our species has been contemplating since the dawn of humanity. These questions include:

(1) Where did it all come from? Astronomy seeks to provide answers by studying the Big Bang, and by investigating hidden aspects of the nature of our physical Universe, including Dark Matter (DM) and Dark Energy.

(2) How did it all form? The Grand Architecture of the Universe is probed by studying the formation, evolution, and structure of galaxies, stars, and planets.

(3) How does it all work? Modern astronomy probes physics in extreme physical environments and operates at the interface between the very large and the very small, unifying particle physics and cosmology, and pushing the boundaries of knowledge.

(4) Are we alone? We are on the cusp of finally providing answers to age-old questions about the nature of life in the Universe, as we embark on the golden age of extra-solar planet discovery.

Canadians have played a leading role on the world stage in many of these areas. Canadian astrophysics is one of our nation's premier sciences. On a normalized citation basis Canadian astronomy has consistently ranked at (or close to) No. 1 within the Group of Eight (G8), and the Council of Canadian Academies assessed Astronomy and Astrophysics as one of nine sub-fields in which Canada is a world leader. The subject is clearly topical and important: in the last 20 years the Nobel Prize in Physics has been awarded four times for research in astrophysics (in 2002, 2006, 2011, and 2015; the latest award included a Canadian who won it for investigation of Solar neutrinos). Graduates of astronomy programs consistently contribute to Canada's innovation agenda by taking technology and data analysis skills into new domains of application. From a hardware development perspective many of the technologies instigated for astronomy find applications within remote sensing and precision engineering arenas, and a recent independent study (the 2015 Doyletech study commissioned by the National Research Council of Canada (NRCC)) places the overall value of these markets at hundreds of billions of dollars.

Canadian Space Astronomy priorities are determined by an exhaustive community consultation process organized by CASCA, and coordinated along with priorities of ground-based astronomical facilities. This "LRP Process" culminated in the 2010 Long Range Plan (LRP2010), which developed a compelling and exciting decadal vision for Canadian astronomy. In the years since LRP2010 significant changes have occurred in the research landscape, and a Mid-Term Review (MTR) of the plan was recently completed (MTR2015). Driven first and foremost by priorities of scientific excellence, and maintaining Canadian astronomy's competitiveness in international astronomy, the planning process pays careful attention to priorities outlined within the Canadian government's science and technology strategy. The overall plan is highly coordinated, covering a breadth of science areas, funding of facilities on various scales, and maximizing science and technological return on investment. Withdrawals from older facilities, as new ones begin operation, are also advocated within the LRP process.

It is understood that revisions of recommendations may be necessary on short timescales due to unanticipated events or developments in the subject, which can be very fast-moving. Established in 2010, the Long Range Plan Implementation Committee (LRPIC) is the body responsible for this oversight for adapting the current iteration of the LRP to the evolving landscape of astrophysics.

All this organizational activity is in service of obtaining maximum value for Canada's investment in space science. Canadians can take pride in our country's achievements in space-based astrophysics. Access to space is key to our understanding of the Universe, and has expanded human thought at a fundamental level, with Canada being a front-and-centre participant in this ennobling and extraordinarily exciting human activity. Canadians have harnessed the advantages of space to help humanity better understand how and when the Universe began, how it evolved, how it produced our home planet, and whether other life exists. These are fundamental questions that characterize our civilization and interest all people, and in particular, young people. Astronomy's broad public appeal is a well-known gateway into STEM disciplines, and the many successes flowing from Canadian astrophysics touch the lives of literally millions of Canadians and resonate down the generations.

To give a specific example, Canada was a partner in the NASA Far Ultraviolet Spectroscopic Explorer (FUSE) mission, beginning in 1987 for its 1999-2007 operational lifetime. Canadians were authors on hundreds of research papers, and Canadian industry was recognized for this contribution. Similarly, Canada is a partner in the current Indian Space Research Organisation (ISRO) Astrosat mission, launched in 2015, having provided vital hardware developed over more than a decade before. The Canadian-led Microvariability and Oscillations of STars (MOST) mission probed the internal structures of stars and its timing allowed it to exploit the new field of exo-planet transits, laying the groundwork for much more ambitious satellites, such as NASA's Kepler. In terms of innovative hardware, MOST was able to obtain dramatically better pointing accuracy than previous micro-satellites, a technology that has been transferred to other projects, such as the BRight Target Explorer (BRITE) nanosats.

Nearly two decades ago the CSA began participating in the development of the JWST, in partnership with NASA and the European Space Agency (ESA). This promises to be an amazing mission and the next few years are likely to be excellent ones for space-based astronomy in Canada. The CSA has played an important role in the development of the JWST mission and, when the spacecraft launches in 2018, Canadians will be justifiably proud to learn that a team of Canadian academic, governmental and industrial scientists, engineers and technicians built one of JWST's key instruments (the Near Infrared Imager and Slitless Spectrograph (NIRISS) spectrometer) and the critical component that points and guides the telescope.

Unfortunately, JWST will have a very limited lifetime. It is designed to have at least a five-year lifetime after launch, and carries only enough fuel to maintain orbital positioning for a little over ten years. Of course, most space-based endeavours have long lead times, and investments in space missions frequently begin to pay off many years into the future (and, when it comes to flagship missions, sometimes decades into the future). The spectacular near-term future we are anticipating with JWST is thus the product of investments begun many years ago.

But what about the decades after JWST? In this document, we map out a future direction for Canadian Space Astrophysics - a future in which Canada innovates, leads and inspires. Operating in synergy with CASCA's LRP, we lay out a roadmap to such a future by showing how space-based astrophysical research could operate in the country at a variety of levels, from low-cost, agile balloon-based missions that perform end-to-end experiments on a timescale relevant for the training of graduate students, to focused mid-scale missions that target high-risk/high-return subjects such as primordial gravitational waves from the first few moments after the Big Bang, all the way up to proposed participation in (and potentially leadership in) much more infrequent but highly ambitious facilities that will keep our astronomical research and space industrial communities vibrant long after JWST.

2.1 Cosmology

Community Report from the Space Astronomy Topical Team on Cosmology and the Cosmic Microwave Background

Table 2-1 Space Astronomy - Cosmology Topical Team

Name	Affiliation
Douglas Scott (Chair)	University of British Columbia
Niayesh Afshordi	University of Waterloo/Perimeter Institute
J. Richard Bond	University of Toronto
Scott Chapman	Dalhousie University
Dagoberto Contreras	University of British Columbia
Matt Dobbs	McGill University
Frederic Grandmont	ABB Canada
Mark Halpern	University of British Columbia
Gary Hinshaw	University of British Columbia
Renee Hlozek	University of Toronto
Michael Hudson	University of Waterloo
Kiyo Masui	University of British Columbia
Julio Navarro	University of Victoria
David Naylor	Lethbridge University
C. Barth Netterfield	University of Toronto
Dmitri Pogosyan	University of Alberta
Neil Rowlands	Honeywell
Kris Sigurdson	University of British Columbia
Kendrick Smith	Perimeter Institute
Locke Spencer	Lethbridge University
Keith Vanderlinde	University of Toronto
Ludovic van Waerbeke	University of British Columbia
James Zibin	University of British Columbia

2.1.1 Introduction to Cosmology in Canada

Cosmology is the study of the Universe on the largest scales and at the earliest times. The most important cosmological questions can be split into four main themes:

- understanding how inflation or some other mechanism created the seeds for all the structure in the Universe;
- investigating whether the Dark Energy, which dominates the energy of the Universe and makes it accelerate, is something other than pure vacuum energy;
- determining the nature of the Dark Matter (DM) that holds the structure together and how galaxies form within the network of DM halos; and
- probing the end of the cosmological dark ages, when the first stars and galaxies ionized the Universe.

These questions can be addressed by gathering data over the full range of the electromagnetic spectrum for which space-based instruments play a critical role. But in practice the missions being planned focus on the "microwave" to "optical" wavelength ranges. In particular the CMB can be studied at relatively long wavelengths, as has already been done by the Cosmic Background Explorer (COBE), Wilkinson Microwave Anisotropy Probe (WMAP) and Planck satellites, and additionally by a set of balloon-based experiments (with Canadians involved in Boomerang, E and B Experiment (EBEX), Spider and others). At optical and near-Infrared (IR) wavelengths we have wide and ambitious surveys carried out by the Hubble and Spitzer Space Telescopes, and planned in future from Wide Field Infrared Survey Telescope (WFIRST), Euclid and other space missions. In the direction of optical surveys the questions of Cosmology overlap strongly with those of the Origins initiative.

Additionally there are X-ray missions whose galaxy-cluster-based studies have direct application to cosmological questions, and hence there is synergy with High-energy Astrophysics (HEA) initiatives. Mid-to-far-IR missions are able to study evolving galaxy clustering and star formation and additionally the possibility exists of using gravitational waves to probe the large-scale structure of the Universe. Nevertheless, we will focus here primarily on the CMB and on optical galaxy surveys.

2.1.2 Prioritised List of Objectives

- COS-01 - Cosmic Microwave Background: Probing the Physics of Inflation
- COS-02 - Dark Energy
- COS-03 - The Nature of Dark Matter
- COS-04 - The End of the Cosmic Dark Ages

2.1.3 COS-01 - Cosmic Microwave Background: Probing the Physics of Inflation

2.1.3.1 Beyond the Standard Model of Cosmology

The CMB gives us a "fingerprint" of how variations in temperature have evolved from the earliest times, through the 13.8 billion years of history of our Universe. By studying these "anisotropies", cosmologists have built up a picture in which the entire statistical information content of the CMB sky can be described by just 6 numbers. Data from a series of CMB satellite missions, culminating in the Planck satellite (largely an ESA mission, but with significant contributions from Canadian scientists and support from the CSA), give us high precision for these half-dozen cosmic numbers. These numbers include the fractional content of the energy density (in Dark Matter, Dark Energy etc.), and also a simple description of the earliest variations in density that grew into all of the clusters, galaxies, stars, planets and people that we observe today.

There are two basic quantities in the standard cosmological picture that encompass the nature of these early fluctuations, namely an amplitude and an index that encodes how the amplitude varies between large scales and small scales. So far everything we know about the CMB is consistent with a theoretical picture in which the early Universe (at a time of perhaps 10^{-36} seconds) underwent a period of rapid “inflation”, when quantum fluctuations on microscopic scales were stretched to become variations in the density of regular “classical” matter. If this picture is correct, then we have the beginnings of an explanation of the origin of *everything*!

So how do we test this picture? The promising idea is that a particular kind of pattern in the polarization of the CMB provides a signature of gravitational waves on the largest scales from inflation, which in turn gives us direct information about the nature of physics during the inflationary epoch. The particular polarization pattern being searched for are called “B-modes”, and are the target of many ground-based CMB experiments, as well as proposed and discussed future space missions.

The difficulty is that not only is the “B-mode” signal small (*very* small in fact!), but we view the sky through the “foreground” screen provided by the Milky Way Galaxy in which we live – and the Milky Way makes its own B-mode signal. In fact, a storm of media attention that followed a claimed detection of these primordial B-modes in 2015 was quickly tempered by the realisation that the experiment had probably been confused by mundane Galactic signals.

What is needed to push down the limits of B-mode experiments is to make sensitive maps at a wide range of frequencies, and do so with extreme control of systematics. Some of the frequencies required are only accessible from space, and space also provides the ultra-stable platforms required to make these measurements robustly.

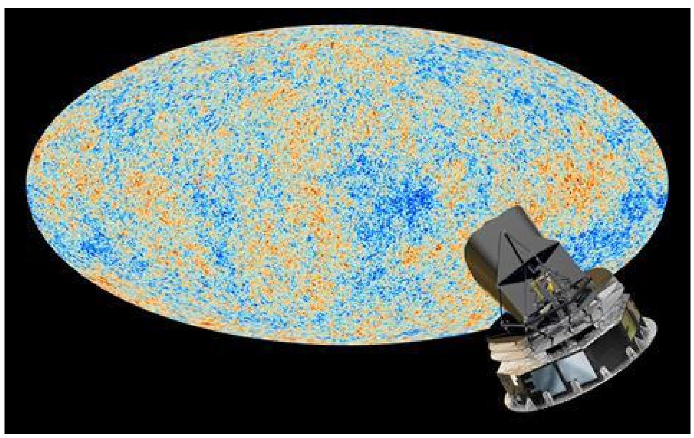

Figure 2-1 This picture of the "Baby Universe" made by the Planck satellite shows the entire sky at a time about 400,000 years after the Big Bang. By carefully studying the statistics of this image we can determine the quantities that describe our Universe on the largest scales. A similar image in CMB polarization would directly probe the physics of the very earliest times. (Source: ESA).

2.1.3.2 Instrument Development for Space: Probing the Physics of Inflation

Our International Partners (IPs) have been busy developing concepts for space missions. Much can be done from balloon platforms, and here Canadians are already engaged, with existing instruments like EBEX and Spider expected to make important contributions. Further balloon experiments are envisioned and these are excellent vehicles, both for trying out novel technologies and experimental strategies, and providing hands on training for the next generation of scientists and engineers.

However, to fully explore the potential B-mode signals, there are ambitious plans underway for a next generation CMB satellite mission. In Japan there is a proposal for LiteBIRD, while in Europe the current incarnation is called the Cosmic Origins Explorer (COrE), and in the USA there is a concept study for a Probe-class mission with the working name of CMB Probe. Canada could be ready to join any of these missions (or their future incarnations).

2.1.3.3 The Canadian Advantage – Alignment with Strategic Planning for Growing Science Capacity and Signature Technologies

Canadians have been involved in most of the major experiments and developments in CMB science, from detector technology and flight hardware to data analysis and theory. Canadian cosmologists are recognised as leading experts in this field, and on that basis are eagerly invited onto international projects. While it is possible for smaller-scale (e.g. balloon-borne) projects to be Canadian-led, the most ambitious projects will be fully international in scope. Nevertheless, the opportunity for Canadian contributions is enormous, and the scope for developing new partnerships also large.

In the university sector, Canadians have expertise in every part of CMB experiments, from basic hardware to software, analysis and science exploitation. As a particular example, Canadians are sought out to provide the multiplexing electronics required for large detector arrays. Moreover, Canadian industry is well-placed to develop and supply the hardware necessary for most of the sub-systems that are needed on future CMB space-based facilities.

While science capacity in cosmology is growing, Canadian researchers are at the forefront, making complementary developments in technology and instrumentation. This opens opportunities that resonate well with the key priorities of Canada's Space Policy Framework. Canadian interests are advanced, since we are a key partner on these international projects. With demonstrated critical-path technologies, doors open for the Canadian private sector to partner with academic researchers in developing and contributing key technology to these large international missions. The large international collaborations and partnerships required by space missions allow Canada to leverage modest investment to yield large returns and enhance the development of Canadian-borne technologies - all serving to open the windows of our understanding of the space environment and the origins of the Universe and inspire our next generation to pursue education in areas of STEM, and consider such careers as viable options.

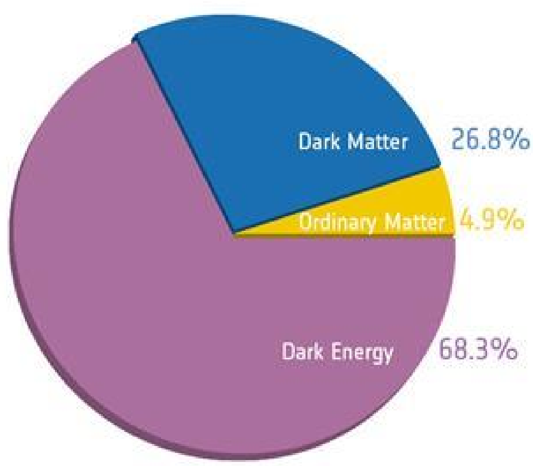

Figure 2-2 This graphic shows the contributions to the energy density budget of the Universe, as determined by the Planck satellite

Approximately 27% is in the form of "dark matter" and 68% is in an even more mysterious component called "dark energy". This diagram illustrates the depth of current ignorance about what makes up most of the Universe - we know how much there is, but we do not really know what these substances are. Future space missions will try to unlock the nature of these dark components. (Source: ESA)

2.1.4 COS-02 - Dark Energy

When a census is taken of the energy contents of the Universe, we find that about 70% is a substance that behaves like vacuum energy, being a uniform fluid with negative pressure, which makes the expansion of the Universe accelerate. Understanding this Dark Energy is one of the greatest mysteries of modern physics. In order to probe its properties we need to determine whether it varies with time, or is constant per unit volume. This comes down to trying to measure the so-called “equation of state” of the Dark Energy, usually denoted by the letter w. If w=-1, then the Dark Energy is pure vacuum energy, or a cosmological constant. But if it deviates from this value, then it would mean that we are dealing with some kind of evolving field that could be connected with a fundamental physics theory. So can we determine if vacuum energy is a constant of nature (the “cosmological constant”) or a time-varying cosmic field? Perhaps it is our theory of gravity that needs to be modified and Einstein’s General Relativity itself is incorrect on the largest cosmological scales.

Current evidence for Dark Energy comes from a combination of CMB measurements, and supernova brightnesses, as well as new methods, which are growing in importance. In particular there is “weak gravitational lensing” (WL), where light from distant objects is slightly bent by gravity around more nearby (but still at cosmological distances) objects. By making lensing measurements in detail we can effectively use a “standard ruler” at a set of distances to use geometry to determine how w varies with time. A second method uses another standard ruler, the “baryon acoustic oscillations” (BAO), which is a particular scale imprinted on the clustering of galaxies and other cosmic structure.

Several missions under development, or under consideration, are aiming to focus on WL and BAO measurements coming from huge optical surveys. In particular there is the NASA mission WFIRST and the ESA mission Euclid.

In fact Canadians are already involved in the Euclid mission, but are playing a minor role on a very large team, and we joined too late to make any hardware contribution. However, for WFIRST there is still an opportunity to join as an important partner.

2.1.4.1 Probing Dark Matter and Dark Energy through the Growth of Structure with Cosmic time

To disentangle the possibilities for Dark Energy and modifications to gravity it is essential to attack the problem through multiple approaches. The classical method is to measure the expansion history of the Universe through standard candles such as Type Ia supernovae, and standard “rulers” such as the scale of baryonic acoustic oscillations. The second approach is to measure the growth of structure with cosmic time: the transition from a smooth early Universe to the clumpy Universe observed today. The latter test distinguishes between simple vacuum energy and alternative theories of gravity.

2.1.4.2 WFIRST

The WFIRST will tackle the dark energy problem using three different, independent methods: supernovae and baryonic acoustic oscillations take the classical approach, whereas weak gravitational lensing is sensitive to the growth of structure with cosmic time. If the answer turns out to be a cosmological constant, WFIRST will measure the key cosmological parameters with incredible accuracy. The multiple approaches will allow strong tests of systematics, which are the dominant sources of error at this level of precision. Of course, if the answer is a time-varying dark energy component, or an alternative to General Relativity (GR), the results will be revolutionary.

Moreover, the gravitational lensing component will measure the spatial distribution of dark matter with unprecedented depth and accuracy, enabling tests of the properties of dark matter, such as its self-interacting cross-section and potentially the mass of the DM particle.

(Additional information on WFIRST is provided in the “Canadian Investigations of our Cosmic Origins” section of this document, Section 2.2.4.)

2.1.4.3 The Canadian Advantage – Alignment with Strategic Planning for Growing Science Capacity and Signature Technologies

Canadians have long been scientific leaders in the areas of supernovae and weak lensing, as demonstrated by their command of the world-leading surveys based on the Canada-France-Hawaii Telescope (CFHT) Legacy Survey (CFHTLS): the Supernova Legacy Survey (SNLS) and CFHTLenS for weak lensing. Scientific involvement in WFIRST will allow Canadians to maintain this leadership in these areas (as well as in other areas of interest to Canadians, such as exoplanets). The studies of contributions to the Integral Field Channel (IFC) and the Relative Calibration System of WFIRST also build up important expertise in space instrumentation at University labs in Canada.

The instrumentation hardware proposed as a WFIRST contribution builds upon the expertise of Canadian companies in space and ground-based astronomy.

2.1.4.4 Current Status and Position within the Canadian Science Roadmap

WFIRST has a very broad appeal across the Canadian community, with about 60 permanent faculty/staff (a significant fraction of the entire astronomical community) expressing strong interest in WFIRST science. The 2010 LRP of Canadian astronomy, after extensive consultation with the Canadian astronomical community, recommended participation in a Dark Energy mission as the top priority in space. The MTR focused this recommendation specifically on the WFIRST mission. It is worth reproducing the recommendation of that report in full.

> *"The Mid-Term Review Panel thus reaffirms the exciting opportunity presented by WFIRST and its broad appeal to the Canadian community. In order to fulfill the Long Range Plan Panel recommendation we recommend that Canada begin negotiations to secure a significant (~5%) level of participation, at the earliest opportunity, so as to match NASA's accelerated schedule. This should include contributions to critical instrumentation that, preferentially, is synergistic with Canadian science interests, and funded participation on Science Investigation Teams for a representative number of Canadian scientists."*
>
> *- CASCA Mid-term Review (2017)*

2.1.4.5 Summary

Dark energy and dark matter are the biggest mysteries in physics. WFIRST is a flagship NASA mission, and the top recommendation of the U.S. Decadal Survey of 2010. It is also the top Canadian recommendation in space of the MTR panel. It promises world-leading measurements of dark energy and dark matter through three probes: weak gravitational lensing; clustering of galaxies; and supernovae. WFIRST is currently on track for launch in 2025. It is essential that Canada secure substantial participation in this mission for Canadian scientists and Canadian industry.

2.1.5 COS-03 - The Nature of Dark Matter

Most of the matter in the Universe is not just regular atoms, but is in some more unusual form, whose nature is unknown. It is “Dark Matter” (DM), which has gravitational effects, but no interaction with ordinary electromagnetic radiation and only very weak interactions with regular atoms. We know (from the CMB, gravitational lensing, X-ray studies and other methods) that there is about 5 times greater mass density in the DM as there is in atoms. But we know little else about it – in particular how it relates to extensions beyond the kinds of particles we know from the standard model of particle physics. DM is thought to be a so-far undetected subatomic particle, but its mass and interaction properties are unknown.

Because its nature is still a mystery, there are several different avenues for exploring the properties of DM.

(1) Does the DM have measurable properties?

By performing detailed WL and BAO measurements, as well as further probing the CMB, we hope to determine if the DM annihilates, decays, or has a self-interaction that is detectable.

(2) What is the fraction of neutrinos?

Measurements of the CMB anisotropies at small angular scales, in particular the lensing effects on the CMB, together with measurements of galaxy clustering at small scales, can be used to determine the overall abundance of DM in the form of neutrinos. In fact these probes are sensitive to the total mass of all neutrino flavours, which is something that is quite complementary to the measurements made by conventional neutrino detectors.

(3) How does DM interact with regular matter?

Ordinary (or baryonic) matter is much more complicated in its behaviour than DM. The DM grows under gravity from small contrast beginnings to form a network of halos, connected by filaments and sheets. Understanding how the baryons clump within these DM halos is crucial for understanding how galaxies form. Wide galaxy surveys allow us to track how the baryons populate DM halos and develop into today's galaxies.

These goals can be achieved through a combination of space-based optical telescopes (such as WFIRST and Euclid) and CMB experiments, as well as their ground-based counterparts.

2.1.6 COS-04 - The End of the Cosmic Dark Ages

The early Universe was very nearly uniform, and hence simple. As the expanding Universe cooled, the ions of the plasma were able to grab electrons and form neutral atoms. This happened at about 400,000 years after the Big Bang – an epoch we observe through the CMB. At later epochs the Universe became neutral, and structure slowly formed, through a period referred to as the “Cosmic Dark Ages”. Eventually the first stars and Active Galactic Nuclei (AGN) formed, producing light that reionized the Universe. Precisely when (and how) this happened is not known.

There are several ways to probe the end of the Dark Ages and what is called the Epoch of Reionization. One method is to measure the scattering effect on the CMB at large angular scales. Another is to search for individual objects at the largest distances (and hence earliest times). So again we are talking about a combination of CMB measurements and wide galaxy surveys with the best space-based facilities. A third method relies on tracking redshifted radio emission from neutral hydrogen - an area of ground-based astronomy in which Canadians are already playing a leading role.

NASA is currently investigating an ambitious mission called the Large Ultraviolet Optical Infrared (LUVOIR) Surveyor, which is one future possibility for a space-based project that will probe the earliest objects in the Universe. (This topic is further discussed in the "Origins" section (2.2) of this document.)

2.1.6.1 Instrument Development for Space: End of the Dark Ages

There are prospects for Canadian contributions to the next generation CMB satellite, whether that is led by Japan, Europe or the USA. It is important to be ready to make an interesting and meaningful contribution to such a mission, whenever it gets the go ahead.

Additionally there are indirect constraints on the shape of the “epoch of reionization” (EoR) from performing a careful census of the earliest objects, as well as by observing the phase transition in hydrogen at this epoch. Hence, a combination of optical/IR and radio observations complement those obtained from the CMB.

JWST will position Canada at the cutting edge of research into the first objects that formed in the history of the Universe. There we provided the Fine Guidance Sensor (FGS) and the NIRISS. This positions Canada well for future missions, such as LUVOIR.

Early objects, particularly in optically-obscured regions, can also be probed through longer wavelength spectroscopy. This is one of the main science drivers behind the Japan Aerospace Exploration Agency (JAXA)-led Space Infrared Telescope for Cosmology and Astrophysics (SPICA) mission, as well as the further-future NASA-led plan for the Origins Space Telescope (OST).

2.1.6.2 Current Status and Position within the Canadian Science Roadmap

These goals fit exactly within the main themes of Canadian Astronomy planning. Canadians played an important role in the CMB Planck satellite, and hence there is expertise for working on the next satellite mission. This particular science area also builds on Canada's strengths in radio astronomy, which is a complementary way to probe the EoR. Canada is leading the Canadian Foundation for Innovation (CFI)-funded Canadian Hydrogen Intensity Mapping Experiment (CHIME) project (which probes neutral hydrogen at somewhat lower redshifts) and Canadians are involved in experiments to use radio observations to probe the EoR. Probing the earliest objects is something that aligns naturally with the “Origins” theme of former Canadian Astronomy LRPs. It can be accomplished through JWST and its successors, e.g. LUVOIR, as well as far-IR missions, in particular SPICA and the OST.

2.2 Canadian Investigations of our Cosmic Origins

Community Report from the Space Astronomy Topical Team on Cosmic Origins

Table 2-2 Space Astronomy - Cosmic Origins Topical Team

Name	Affiliation
Roberto Abraham (Chair)	University of Toronto
Michael Balogh	University of Waterloo
Pauline Barmby	Western University
Stefi Baum	University of Manitoba
Ilaria Caiazzo	University of British Columbia
Ryan Cloutier	University of Toronto
Patrick Cote	Herzberg Astrophysics
Nick Cowan	McGill University
Sara Ellison	University of Victoria
Laura Ferrarese	Herzberg Astrophysics
Sarah Gallagher	Western University
Frederic Grandmont	ABB Canada
Jeremy Heyl	University of British Columbia
John Hutchings	Herzberg Astrophysics
Michael Hudson	University of Waterloo
David Lafrenière	Université de Montréal
Christian Marois	Herzberg Astrophysics
Brenda Matthews	Herzberg Astrophysics
Alan McConachie	Herzberg Astrophysics
Stan Metchev	Western University
Max Millar-Blanchaer	California Institute of Technology
Barth Netterfield	University of Toronto
Laura Parker	McMaster University
Alan Scott	Honeywell
Chris Willott	Herzberg Astrophysics
Harvey Richer	University of British Columbia
Neil Rowlands	Honeywell
Luc Simard	Herzberg Astrophysics
Warren Soh	Magellan Aerospace
Diana Valencia	University of Toronto
Kim Venn	University of Victoria
Christine Wilson	McMaster University

2.2.1 Introduction

The Universe expanded rapidly from an extraordinarily hot and dense state billions of years ago; this central tenet of modern cosmology is called the hot Big Bang model. This is consistent with a variety of observations, including the expansion of the Universe discovered by Edwin Hubble in the 1920s, the abundance of light elements in the Universe, and the cosmic microwave background radiation that floods our sky, and is described in detail in the Cosmology TT community report (section 2.1).

The Universe created in the Big Bang is defined by a fundamental simplicity – it is almost the same at every point in space, with only tiny amplitude variations from place to place. The “Origins” theme takes over once this era of simplicity ends. In other words, the Big Bang set up the laws of physics, and it made the mysterious dark matter that dominates the mass of the Universe, creating the hydrogen and helium that constitutes most of its atomic content. But everything else in the wonderfully rich, complicated, strange Universe we are familiar with emerged later, by a process of gradual evolution. So, when astronomers refer to the study of origins, they refer to the study of the processes by which complexity emerges from the simple Universe put in place at the earliest times. How did our Universe become filled with material objects on an astonishing, almost incomprehensible range of scales, containing phenomena as varied as life (from 10^{-6} to 10 m in size), planets (10^{3}–10^{5} km in size), stars (10^{6}–10^{9} km in size), galaxies (10^{16}–10^{18} km in size), and clusters and super-clusters of galaxies (10^{19}–10^{20} km in size)?

Astronomy continues to lead the world in new, inspiring discoveries related to our cosmic origins, and Canadian astronomers continue to be major players in most of these. A few recent examples from among many will illustrate the international stature of Canadian astrophysics in Origins-related research activity.

(1) Dark Energy

In 2011 the SNLS team published the results of a huge imaging survey with the CFHT designed to detect distant supernovae, followed up with spectroscopy from the Gemini, Very Large Telescope (VLT) and Keck telescopes. When combined with results from WMAP and other projects, the precision to which several of the fundamental parameters of the Universe could be constrained was truly remarkable, e.g. the overall matter density to within 5%, and the dark energy equation of state parameter (which measures the ratio of the energy’s pressure to density), to within 6.5%. It is worth bearing in mind that just two decades ago these numbers were not even known to within an order of magnitude! While Dark Energy is primarily discussed in the Cosmology TT Community Report, there are significant areas of overlap with the Origins theme (because in order to measure Dark Energy one first needs to account for the properties of the foreground signals, including galaxies and dust), and which will be described below.

(2) Galaxy Formation and Evolution

The results of another major survey with the CFHT, the Pan-Andromeda Archaeological Survey (PAndAS), revealed a substantial population of dwarf satellite galaxies around M31 as well as streams of stars that are obviously the results of interactions with such galaxies in the past. A Nature paper in 2013 detailed results showing, highly unexpectedly, that the dwarf satellites are located in a remarkably thin co-rotating plane. Surveys like this one of other nearby galaxies have the potential to reveal how galaxies form from DM halos, especially when combined with kinematic and age determinations from upcoming massive spectroscopic surveys.

(3) Exoplanets

Results from the Gemini Planet Imager (GPI), an "extreme adaptive optics system," on the Gemini South telescope are also starting to appear. Engineers and scientists at the Université de Montréal and National Research Council (NRC) Herzberg played very major roles in this instrument and Canadian scientists are already reaping the rewards. One of the most exciting discoveries so far is a planet that appears to be very similar to Jupiter orbiting the star 51 Eridani about 100 light years away. Stellar age estimates suggest that 51 Eridani is only around 20 million years old, making this a young planetary system that can help shed light on planet formation processes. Theoretical models suggest the gas in giant planets can be accreted in ways that lead to a "hot start," in which gravitational energy is trapped making the infant planet hot, or a "cold start" in which accreting gas is shock heated allowing it to radiate away a lot of the energy. Almost all observations to this point had been too bright to be considered cold-start candidates. Intriguingly, the planet, denoted 51 Eridani b, has the strongest methane signature of any extrasolar planet and is also of sufficiently low luminosity to possibly be a cold-start candidate. The observed luminosity suggests that the mass of the planet is between 2 and 12 Jupiter masses in cold-start scenarios. Alternatively, if a hot start is assumed, the mass is around 2 Jupiter masses. The discovery garnered considerable attention and was outlined in an important article in Science magazine.

Canadian astronomers also used the GPI and Keck telescopes to study the chemical composition and atmospheric structure of two of the planets surrounding HR 8799, one of the discoveries highlighted in LRP2010. The ability to perform detailed studies of other extra-solar planets like those around HR 8799 and proto-planetary disks like HL Tau is certain to be transformative in our understanding of the origin and evolution of planetary systems and, indeed of Earth-like planets. Observations with Atacama Large Millimeter/submillimeter Array (ALMA), JWST and Thirty Meter Telescope (TMT) will be of paramount importance in this quest. As an example of the synergy, ALMA and JWST can study the outer, colder regions of proto-planetary disks, while TMT will provide a direct look at the inner, warmer regions where terrestrial and giant planets form. Spectra of gaseous lines with JWST will provide critical velocity information to understand the radial distribution of the gas, and how the dynamical, chemical and physical structures of these disks will evolve with time.

(4) The Interstellar Medium

Canadians were important participants in the Planck and Herschel satellites that were launched in 2009. Both missions were outstandingly successful and the results continue to rank among the highest impact areas in astrophysics in Canada. Canadians led important investigations of the interstellar media using both missions. Planck data were analyzed to uncover dust properties throughout the Milky Way Galaxy. Indeed, the key cosmological results from Planck would not have been possible without such careful knowledge of this bright foreground. Herschel uncovered the filamentary structure within molecular clouds and revealed their important connection to star formation. Herschel also analyzed the many roles that water plays in star formation, acting both as a major radiative coolant and a key player in astro-chemistry. Scientists from both academia and industry played major roles in several areas, including hardware, theory, algorithms, reduction, experience and expertise. The results still pouring out of Planck and Herschel demonstrate that the $21M contributed by Canada through CSA was exceedingly well spent.

2.2.2 An Ecosystem for Canadian Participation in Space Astronomy

The CSA is contributing to the JWST in the form of a $170M investment in NASA's flagship mission. Canadian participation in the JWST is a major achievement in Canadian space astronomy, generating enormous interest within the scientific community, whilst simultaneously being the most complex and ambitious space astronomy project attempted – in Canada and worldwide. CSA's support of JWST, and FUSE and Astrosat before that, has enabled Canadian industrial partners to develop world-leading expertise in key space technologies, such as precision guiding, ultraviolet (UV) photon-counting detectors, IR detector operations, and cryogenic systems. Where do we want to go next?

Because of our substantial contributions to the JWST, the technological and management capabilities of Canadian space contractors, as well as the aspirations of Canadian scientists, have grown hand-in-hand. As has been highlighted at length in the CASCA LRP and its MTR, the potential of Canadian space astronomy, both in terms of science leadership and industry expertise, has reached the point where leading a mid-level space astronomy mission is an achievable and natural next step. At the same time, Canada's capability to undertake such a mission has emerged as the product of a long history of participation in international missions.

This is a critical point – because of the long timescale associated with the development of flagship missions and the need for specialized engineering and technical expertise, non-participation in these international missions in order to fund a flagship mission every one or two decades (opportunities for which arrive with a frequency needed to maintain technical expertise and a broad skills and training "ecosystem") one cannot simply undertake flagship missions every couple of decades and maintain a robust space astronomy program.

The key notion is the need for maintenance of a balanced ecosystem of space-based activity on a range of scales. It is therefore notable that while Canada has had a track record of impressive contributions to international space astronomy missions, the window is closing fast for a Canadian contribution to NASA's dark-energy flagship mission WFIRST and for the ESA X-ray flagship mission Advanced Telescope for High ENergy Astrophysics (Athena). It is paramount that Canada be ready to commit to such opportunities when they arise to ensure that the space science and engineering community of today will remain in Canada, and that the community of tomorrow has the capacity to continue to push the limits of exploration.

Leadership in a mid-level mission should be viewed as both our top priority and as a component of a sustainable ecosystem for engagement in Space Astronomy missions. To succeed in maintaining its leadership position in a program to understand our origins, Canada must continue to develop expertise in critical areas of space astronomy, by participating at a partnership level in missions led by other national agencies, and by using small satellites and balloon-borne instruments to undertake exciting and focused experiments on timescales relevant for the training of the next generation of scientists. Success requires an environment that fosters scientific and engineering innovation, which in turn requires maintenance and growth in the form of substantive and reliable injections of resources.

In the following sections, we present a set of six space astronomy missions in which Canadians have significant interest. These missions include both early concepts that are at least a decade away (LUVOIR, Habitable Exoplanet Imaging Mission (HabEx), OST) and highly developed missions almost ready for construction (Cosmological Advanced Survey Telescope for Optical and UV Research (CASTOR), WFIRST, SPICA). The missions presented are not a complete or exclusive list of space missions, and they should be considered in a context that includes the reports from the other CSA TTs. Of course, as new opportunities emerge, it will be important to maintain contact with these initiatives.

In considering this set of missions, two important points should be borne in mind:

(1) Early engagement is critical for securing a significant voice in scientific direction and overall capabilities of missions, and for ensuring that both are aligned with Canadian interests (in terms of scientific and industrial capacity).

(2) The very long lead times involved in space astronomy, coupled with the specialized knowledge and skills needed, requires sustainable activity occurring with a somewhat regular cadence over a planning horizon that stretches at least a decade to maintain significant capacity. The importance of viewing a balanced portfolio of small, medium, and large missions as components of a space astronomy ecosystem will be emphasized repeatedly in this document.

2.2.3 CASTOR: A Flagship Canadian Space Telescope

2.2.3.1 The Scientific Landscape of Astronomical Surveys in the 2020s

In the next decade, two landmark space missions will transform astronomy by carrying out deep, high-resolution, wide-field imaging in the red-optical and IR spectral region ($0.55\ \mu m \leq \lambda \leq 2\ \mu m$). The first of these, Euclid, is an ESA-led mission that is scheduled for launch in 2020. Euclid will image an area of at least 15,000 square degrees at near-IR wavelengths, as well as in a single broad filter (Visible (VIS)) at red-optical wavelengths. Around 2023, Euclid will be joined by NASA's WFIRST mission (scheduled for launch in the mid-2020s), which will also carry out red-optical/IR imaging (YJH and F184W) to a depth about 2 times deeper than Euclid over a smaller (2200 square degree) field. Both missions are primarily motivated by a desire to understand dark energy, but their legacy value is so immense that a vast amount of ancillary science will be enabled.

On the ground, the Large Synoptic Survey Telescope (LSST) is expected to begin its decade-long survey operations in 2022. LSST will revolutionize time-domain astronomy by repeatedly imaging an area of half the sky (20,000 square degrees) every few nights. The combination of optical imaging from LSST and IR imaging from Euclid/WFIRST will be a powerful resource that astronomers will exploit for decades to come, but taken together these facilities leave a huge gap in our knowledge, as their focus on near-IR wavelengths means that the Universe at ultraviolet wavelengths will be almost entirely neglected. This represents a spectacular opportunity for Canadian astronomy to make a huge impact by taking the lead on a relatively modest space mission.

2.2.3.2 The Ultraviolet: A Treasure Trove of Astrophysics

Because Earth's atmosphere is opaque to ultraviolet light, the UV regime is almost completely unexplored, even though it has a special significance in astronomy, since it contains a wealth of information on the physical properties of gas, stars and galaxies. This region is especially important for characterizing emission from young and/or hot stars, as well as from hard non-thermal sources, such as AGN. For galaxies, UV/blue-optical coverage is critically important when estimating distances from so-called "photometric redshifts", and accurate photometric redshifts are a prerequisite in the use of weak lensing as a dark energy probe (a key element of both the Euclid and WFIRST missions). Furthermore, most of the baryons (regular material made up of atoms, as opposed to exotic material such as DM) in the Universe exists in between galaxies (and not in galaxies, as commonly claimed), as a hot, diffuse gas known as the Warm-Hot Intergalactic Medium (WHIM), which floods the Universe while being held within a gravitational framework known as the Cosmic Web. This important aspect of the Universe is very poorly understood because it is mainly detectable through very weak ultraviolet emission lines.

2.2.3.3 The CASTOR Mission Concept

The CASTOR is a proposed CSA-led mission that would carry out panoramic imaging in the UV and blue-optical region (150–550 nm). Operating close to the diffraction limit, the 1-m CASTOR telescope would have a spatial resolution comparable to the Hubble Space Telescope (HST), but with an instantaneous Field of View (FOV) about two hundred times larger. The scientific impact from such a facility would be immense, covering topics ranging from small bodies in the outer solar system to the equation of state of the Universe. CASTOR has the potential to be a significant, unique and highly strategic Canadian contribution to the international portfolio of astronomical facilities in the 2020s, complementing the high-profile optical/IR space- and ground-based missions just described (Euclid, WFIRST and LSST) and currently under development in Europe and the US. By placing Canada at the forefront of astronomical research in the coming decade, CASTOR would showcase the technological capabilities of Canadian industries to an international audience, and inspire the next generation of young Canadians to pursue careers in science, engineering and technology.

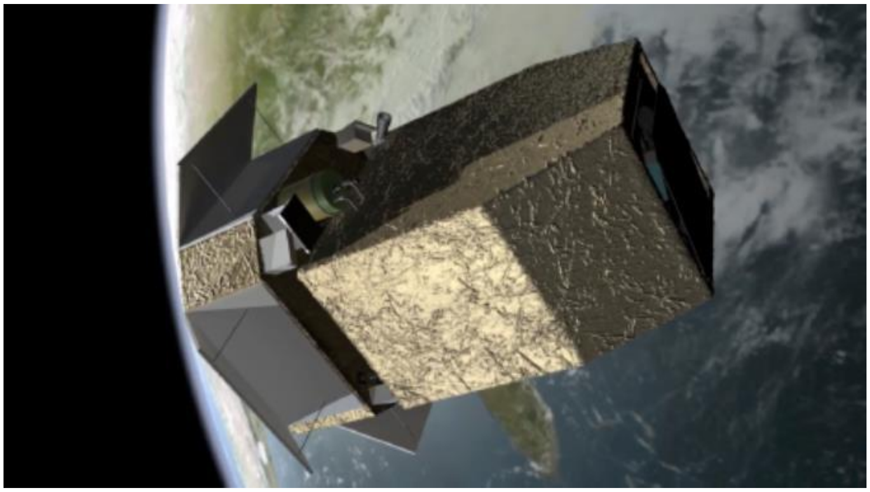

Figure 2-3 CASTOR is a proposed CSA-led 1250 kg 'smallSAT'-class 1-m unobstructed aperture space telescope mission designed to meet distinct and far-ranging scientific goals by virtue of a simple but innovative design and a flexible operations model. These include characterizing the effects of dark energy on the cosmos, understanding the history of galaxy evolution and star formation, and detecting the most distant objects in our solar system. The spacecraft is designed to be compatible with multiple launchers (i.e. Polar Satellite Launch Vehicle (PSLV), Falcon 9, etc.) and will operate in a sun-synchronous polar orbit with an altitude between 600 and 800 km. (Source CSA)

CASTOR has been specifically designed to provide the "missing" capabilities in world-astronomy set in place by Euclid/WFIRST/LSST that will be urgently needed in the 2020s: i.e. access to the UV region, high blue sensitivity and observing efficiency, and superb angular resolution over a large instantaneous FOV. It would thus be a strategic asset that might be used to negotiate some level of Canadian involvement in LSST, Euclid and/or WFIRST in exchange for European/US involvement in CASTOR. CASTOR would also offer a powerful complement to JWST. This major international mission (a collaboration between NASA, ESA and CSA) is scheduled for launch in 2018. It will focus on the red-optical/IR region to explore "first light" and reionization in the early Universe. By doing so, it will be observing these galaxies, stars and quasars at rest-frame UV wavelengths. Thus, UV/blue-optical emission from sources in the relatively nearby Universe is certain to take on a renewed importance in the post-JWST era. Farther ahead, CASTOR could serve as an important scientific and technical pathfinder for the next generation, large-aperture (8-16m) UV/optical/IR space telescopes. Such a facility has emerged as a leading candidate for a possible NASA flagship mission in the post-2030 era.

2.2.3.4 The Canadian Advantage

CASTOR provides a unique opportunity for academia, industry and government to join forces on a project whose benefits to Canada would far surpass those that might be achieved through small partnerships in one or more international projects. We note that the overall cost to Canada would likely be comparable to its contribution over the past decade to JWST — the centrepiece of a multi-scale and multi-wavelength Canadian space portfolio that included MOST, FUSE, Astrosat, Herschel, Planck, Balloon-borne Large-Aperture Sub-millimeter Telescope (BLAST), Near-Earth Object Surveillance Satellite (NEOSSat), BRITE-Constellation, as well as several other balloon and space missions that are currently in development.

Released in February 2014, Canada's Space Policy Framework, was developed to identify priorities and guide activities in space in the coming years. CASTOR's alignment with its five "guiding principles" is remarkable.

- ***Theme 1. Inspiring Canadians.*** As the world's preeminent blue-optical/UV imaging telescope, CASTOR would combine the wide-field and high-resolution elements of HST and CFHT imaging that has been so effective in capturing the imagination of the public. It would allow CSA to play a leading role in communicating the importance of science, engineering and technology to the Canadian public and would almost certainly supplant Alouette 1 and Canadarm as the most visible space project ever undertaken by Canada.

- ***Theme 2. Excellence in Key Capabilities.*** CASTOR would provide a natural next step in the growth of Canada's space hardware sector. Industries that participated in the development of smaller missions, and/or collaborated on large international projects like JWST, have developed unique expertise in the design, development, testing and fabrication of electro-optical payloads and large focal plane arrays. Moreover, by positioning Canadian astronomers, physicists, engineers and software developers at the leading edge of their professions, it would help ensure that the next generation of scientists and engineers are retained in Canada.
- ***Theme 3. Progress through Partnerships.*** By its very design, CASTOR has strong scientific synergy with Euclid, LSST and WFIRST — three of the highest-priority projects planned for the 2020s by the European and American astronomical communities. It would thus foster closer scientific, industrial and programmatic partnerships with these two important communities. CASTOR also represents the next step in wide-field UV imaging, begun by Galaxy Evolution Explorer (GALEX), and continued now by our share of UltraViolet Imaging Telescope (UVIT) on Astrosat. By the time CASTOR flies, it will replace all of these, as well as HST, and serve an enormous scientific community.
- ***Theme 4. Positioning the Private Sector at the Forefront of Space Activities.*** A preliminary evaluation of the potential impact of CASTOR on the high-tech industrial sector in Canada identified about two dozen companies — geographically distributed from coast to coast — that might participate in the design, development and fabrication of the mission. This level of industrial impact is unique to a scientifically ambitious and technically demanding project like CASTOR. As noted in the CASCA LRP, CASTOR would provide "the ideal opportunity for high-tech Canadian companies to showcase their capabilities", particularly in the areas of opto-electronics, high-volume data transmission technologies, X-band phased array transceivers, data handling units, memory boards, readout systems, and control software.
- ***Theme 5. Canadian Interests First.*** As is the case with other developed nations, Canada's future sovereignty, security and prosperity are likely to rely increasingly on an active and vibrant space program. Space astronomy occupies a special place within the portfolio of most national space agencies (e.g. NASA, ESA, JAXA, ISRO) as it is arguably the most visible of endeavours, with public broad appeal and large scientific and industrial returns.

2.2.3.5 Current Status and Position within the Canadian Science Roadmap

The CSA-sponsored Discipline Working Group on wide field imaging in space was completed in 2009, and proposed CASTOR as a 1m-class imaging space telescope to observe in UV and blue wavelengths. CSA funded a very extensive concept study for such a mission, demonstrating its feasibility and performance. It also showed it to be affordable technically within what Canada could provide. The study was completed in 2012, and in subsequent years became of wide international interest. The science case extends far beyond the Dark Energy connections, as, like HST, the data will be very significant for almost all areas of astronomy research. Later CSA technical study contracts further developed the details and availability of the detectors required, and also the requirements and availability of filters and dichroics essential for good UV imaging. As a result of this work, the telescope design was developed further and costing estimates were made for these elements of the mission.

The community (science advisors, space industry) have strongly recommended that a follow up study be conducted to review the concept, requirements and costing of the CASTOR payload, as called for in the CASCA LRP's MTR. This will involve a science team working with the contractors to update the science case and requirements. Based on a 2017 CSA "Advanced Notice" for a set of up-coming calls for proposals, in about a year, CSA should have the information needed to decide whether to recommend to the government that CASTOR should move to its construction phase.

2.2.3.6 Summary

CASTOR provides a unique opportunity for academia, industry and government to join forces on a project whose benefits to Canada have the potential to far surpass those that might be achieved through small partnerships in one or more international missions. While Canadian-led, CASTOR would certainly include significant IPs, so the Canadian cost as well as schedule will be shared, and under our control. The science enabled by CASTOR has wide international interest, and there are groups in the US and elsewhere working on similar concepts. They are excellent potential partners in a Canadian-led mission, and CASTOR core members are in close touch with several. While encouraging, the situation emphasizes that this opportunity is ours to lose, if we fail to move ahead in a timely way.

CASTOR's overall cost to Canada would likely be comparable to its contribution over the past decade to JWST — the centrepiece of a multi-scale and multi-wavelength Canadian space. The benefits to Canada from CASTOR are spectacularly well-aligned with Canada's Space Policy Framework, and the scientific potential of the mission is unparalleled, encompassing Dark Energy, the detection and composition of remote bodies in the outer solar system, micro-lensing searches for exoplanets, the chronology and mass spectrum of accretion in the Milky Way and nearby galaxies from resolved stellar populations and the definitive characterization of the history of cosmic star formation and its relationship with the Cosmic Web.

2.2.4 *WFIRST: Wide-field Infrared Survey Telescope*

WFIRST is a flagship NASA mission, the top recommendation in space of the U.S. Decadal Survey of 2010 and participation in WFIRST at a significant level is the top Canadian recommendation in space of the 2015 CASCA MTR panel. The mission makes use of an existing 2.4-m telescope, the same size as the HST, but with a FOV about 200 times larger than that of HST. WFIRST is optimized for a dark energy mission, but it will also be the premier space-based observatory for studies of exoplanets, stars and galaxies. WFIRST is currently on track for launch in 2025. The cosmological aspects of WFIRST's science motivation are described in the Cosmology TT report; here we focus on the “origins” aspects.

2.2.4.1 WFIRST and the Origins of Exoplanets, Stars and Galaxies

The nature and origins of planets, stars and galaxies are amongst the most important puzzles in science. The questions posed by trying to understand these structures are fundamental:

- What are other planetary systems like?
- Do they host planets with properties similar to those of planets in our Solar System?
- Are these habitable?
- How did they form?
- How soon after the Big Bang did the first stars and galaxies form?
- How did galaxies assemble and evolve?

2.2.4.2 WFIRST Capabilities for Origins Investigations

WFIRST will study the origins of planets, stars and galaxies by several different methods. WFIRST has two modes: targeted surveys (75%) and proposal-driven guest observer time (25%). WFIRST's Wide-field Channel (WFC) has a FOV 200 times that of Hubble's WFC3 and 200 times that of JWST's NIRCAM. WFIRST will be the premier mission for high-resolution, wide-field imaging in the near-IR.

- ***Exoplanets***: WFIRST will study exoplanets in two unique and complementary ways.

  Firstly, it will conduct a survey of the Galactic bulge with the WFC to detect exoplanets – including free-floating planets – via gravitational microlensing. This will allow it to complete the census of exoplanet systems by studying planets at large orbital semi-major axis (and hence long period), not accessible to the transit or Doppler techniques.

Secondly, it will use the coronagraph to characterize exoplanets in reflected starlight. The coronagraph will reach contrasts as low as 10^{-9} at an inner working angle of <0.2 arcseconds, allowing the study of Neptune-mass planets in wider Jupiter-like orbits for host stars within 10 pc. The coronagraph's integral field spectrograph can then be used to characterize atmospheric composition, including clouds, on such exoplanets.

- ***Stars***: The wide field of WFIRST will allow deep colour-magnitude studies of the Galactic bulge as a by-product of the microlensing survey. The wide field and high angular resolution will resolve stars within our Galaxy's halo and stellar streams and across the tidal streams and halos of nearby galaxies. The resulting near-IR colour-magnitude diagrams will measure ages and metallicities yielding new insights into the assembly history of galaxies.
- ***Galaxies:*** One of the greatest mysteries is the nature of the first galaxies to appear in the early Universe (< 1 billion years, at "Cosmic Dawn"). At present, there are fewer than a dozen very-high redshift (> 9) galaxy candidates. The WFIRST High-latitude Survey will uncover hundreds to thousands of such galaxies and quasars, and make these available for follow-up study by JWST and ground based 30-m class ground-based telescopes.

  WFIRST will also characterize the morphologies of distant galaxies, their DM halos (through gravitational lensing), as well as the low surface brightness features in the nearby Universe with unprecedented depth. Large-scale studies of this type with HST (such as Panchromatic Hubble Andromeda Treasury (PHAT) and Cosmological Evolution Survey (COSMOS)) have been amongst the most-cited HST programs, but have taken many hundreds of orbits. It is remarkable to think that these could be accomplished in only a few orbits with WFIRST.

2.2.4.3 WFIRST as a Probe of Dark Energy and Dark Matter

The current cosmological model contains two components, DM and dark energy, both of which are almost completely unknown. The physical natures of these two components are arguably the two greatest puzzles in Physics today. DM is thought to be a so-far undetected subatomic particle, but its mass and interaction properties are unknown. Even more mysterious is dark energy, which is driving the acceleration of the Universe's expansion. Is it a constant of nature, or a time-varying cosmic field? Or is Einstein's General Relativity itself incorrect on large cosmological scales?

To disentangle these possibilities, it is essential to attack the problem through multiple approaches. The classical approach is to measure the expansion history of the Universe through standard candles such as Type Ia supernovae, and standard "rulers" such as the scale of baryonic acoustic oscillations. The second approach is to measure the growth of structure with cosmic time: the transition from smooth early Universe to the clumpy Universe observed at late times. The latter test distinguishes between Dark Energy and alternative-to-General-Relativity gravity. WFIRST will contribute directly to both of these approaches, using multiple probes.

2.2.4.4 WFIRST Capabilities for Dark Energy Investigations

WFIRST will tackle the dark energy problem by three different, independent methods: supernovae and baryonic acoustic oscillations take the classical approach, whereas weak gravitational lensing is sensitive to the growth of structure with cosmic time. If the answer turns out to be a cosmological constant, WFIRST will measure the key cosmological parameters with incredible accuracy. The multiple approaches will allow strong tests of systematics, which are the dominant sources of error at this level of precision. Of course, if the answer is a time-varying dark energy component, or an alternative to GR, the results will be revolutionary.

Moreover, the gravitational lensing component will measure the spatial distribution of DM with unprecedented depth and accuracy allowing tests of the properties of DM, such as its self-interacting cross-section and potentially the mass of the DM particle.

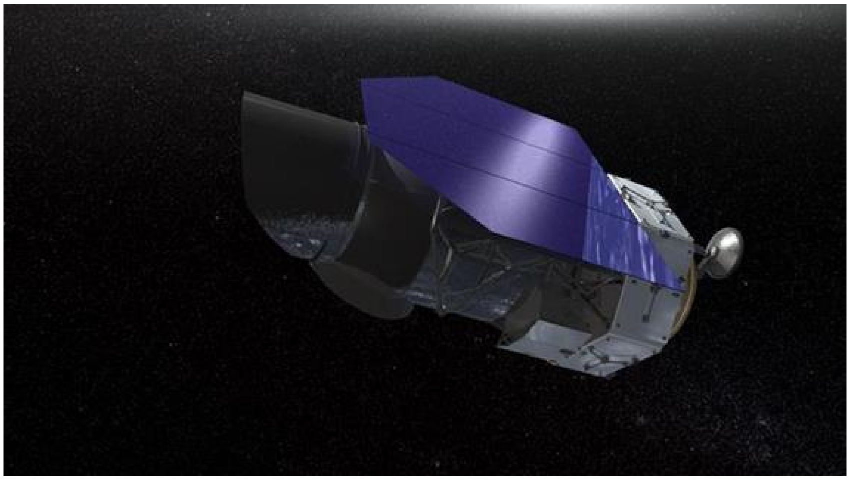

Figure 2-4 WFIRST Concept

WFIRST is a NASA observatory designed to settle essential questions in the areas of dark energy, exoplanets, and IR astrophysics. The current design of the mission makes use of an existing 2.4 m telescope, which is the same size as the HST. The Wide Field Instrument will provide a FOV of the sky that is 200 times larger than images provided by HST. The coronagraph will enable astronomers to detect and measure properties of planets in other solar systems. (Source NASA)

2.2.4.5 The Canadian Advantage

Canadians are world-leaders in astronomy in many of the scientific areas targeted by WFIRST. For example Canadians have led key ground-based studies of the high-redshift Universe (Gemini Deep-Deep Survey) and of the nearby Universe (PanDAS). Canadian astronomers are also pioneers in direct imaging of exoplanets and the data reduction pipelines for such observations. Canadians have long been scientific leaders in the areas of supernovae and weak lensing, as demonstrated by their command of the world-leading surveys based on the CFHT Legacy Survey: the SNLS and CFHTLenS for weak lensing. Scientific involvement in WFIRST will allow Canadians to maintain this leadership in these areas (as well as in other areas of interest to Canadians). The studies of contributions to the IFC and the Relative Calibration System also build up important expertise in space instrumentation at University labs in Canada, not to mention the many university-based institutions and organizations that have emerged as a result of Canadian leadership in astrophysics (Institute for Research on Exoplanets (IREx), Canadian Institute for Theoretical Astrophysics (CITA), McGill Space Institute (MSI), Centre for Research in Astrophysics of Quebec (CRAQ), Astronomy Research Centre (ARC) , Dunlap Institute, etc.). And, of course, the instrumentation hardware proposed as a WFIRST contribution builds upon the expertise of Canadian companies in space and on the ground.

2.2.4.6 Current Status and Position within the Canadian Science Roadmap

WFIRST has a very broad appeal across the Canadian community and aligns perfectly with Canadian astronomical priorities. The 2010 astronomy LRP recommended participation in a Dark Energy mission as the top priority in space and the MTR recommendation underscored this.

> *"The Mid-Term Review Panel thus reaffirms the exciting opportunity presented by WFIRST and its broad appeal to the Canadian community. In order to fulfil the Long Range Plan Panel recommendation we recommend that Canada begin negotiations to secure a significant (~5%) level of participation, at the earliest opportunity, so as to match NASA's accelerated schedule. This should include contributions to critical instrumentation that, preferentially, is synergistic with Canadian science interests, and funded participation on Science Investigation Teams for a representative number of Canadian scientists."*
>
> *- CASCA Mid-term Review (2017)*

Participation in WFIRST is a priority for Canadian astrophysics, but at the same time it is essential that a very minor partnership in WFIRST not be seen as our only space mission for the next decade.

2.2.4.7 Summary

Dark energy and DM are the biggest mysteries in physics. WFIRST is a flagship NASA mission, and the top recommendation of the U.S. Decadal Survey of 2010. It is also the top Canadian recommendation in space of the MTR panel. It promises world-leading measurements of dark energy and DM through 3 probes: weak gravitational lensing, clustering of galaxies, and supernovae. WFIRST is currently on track for launch in 2025. It is essential that Canada secure substantial participation in this mission for Canadian scientists and Canadian industry.

2.2.5 SPICA: Space Infrared Telescope for Cosmology and Astrophysics

2.2.5.1 The Landscape of Mid-Infrared and Far-Infrared Astronomy in the Next Decade

Understanding the origin and evolution of galaxies, stars, planets and life itself is a fundamental objective of Astronomy. Although impressive advances have been made, our knowledge of how the first galaxies and stars formed, and how they evolved into what we see around us today, is still far from complete. A major reason for this is that the birth and much of the growth of galaxies, stars and planets occurs in regions that are hidden by a thick blanket of dust – virtually inaccessible to the visible-wavelength instruments that have been the main tools of astronomers since the invention of the telescope. Observations at IR wavelengths allow astronomers to peer into these obscured regions. The vast array of spectral diagnostics that lie in the mid- to far-IR provide a unique tool for astronomers to determine the physical composition and conditions both in the local Universe and at high redshift. Furthermore, the IR range is where the spectra of many objects peak, as most of their cooling radiation is emitted at these wavelengths, either intrinsically or because of their redshift. For these reasons, investigating the physical processes that define our Universe requires ultra-sensitive observations in the mid- to far-IR, which can penetrate the dust and reveal the inner workings of galaxies, star-forming regions, and planet-forming systems, over much of cosmic history.

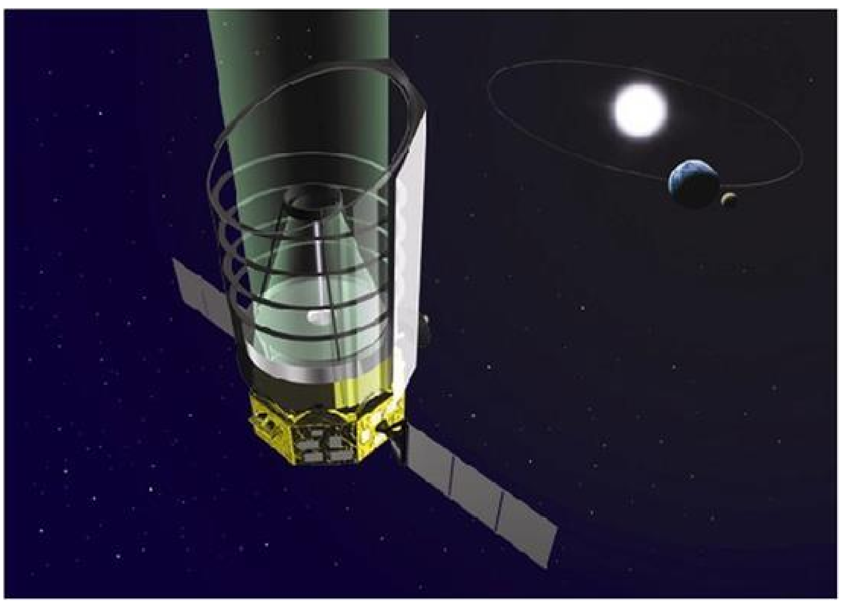

Figure 2-5 The SPICA Space Telescope is a proposed joint Japanese-European project to develop an advanced far-IR space telescope. It will build on the experience gained from Herschel, but will include significant advances in detector and cryogenic technologies to allow it to be more than an order of magnitude more sensitive than Herschel - anything that Herschel could detect, SPICA will be able to obtain a spectrum of it. (Source JAXA)

Building on the success of ESA's Herschel Space Observatory, in which Canada played a significant role on two of the three instruments (Heterodyne Instrument for the Far Infrared (HIFI) and Spectral and Photometric Imaging Receiver (SPIRE)), a joint European-Japanese team has proposed to develop SPICA, and because of our contributions to Herschel, has invited Canada to join in this exciting mission. SPICA is an observatory class mission that is currently under review by ESA (with an anticipated launch date in 2029) as part of its Cosmic Vision M5 call. SPICA will provide imaging, spectroscopic and polarimetric capabilities in the 5–350μm wavelength range. SPICA features a 2.5-m class telescope cooled to a temperature less than 8 K.

The combination of a new generation of ultra-sensitive detectors and effectively zero-background emission from the telescope, will allow astronomers, for the first time, to achieve sky-limited sensitivity over this wavelength range. SPICA will be over two orders of magnitude more sensitive than Spitzer and Herschel, which represents an enormous leap in capabilities to explore the hidden Universe. Moreover, SPICA will cover the full wavelength range between 5 and 350μm, including the missing octave between 28 and 55μm, which lies outside of both the Herschel and JWST domains. Thus, not only will SPICA be the only observatory of its era to bridge the wavelength gap between JWST and ALMA, but it will enable unique science on galaxies, star-forming molecular clouds, and proto-planetary disks. These science areas will be complementary to and not accessible with ALMA.

2.2.5.2 Science Goals: Unveiling the Obscured Universe

A prime goal of SPICA is to reveal the physical processes that govern the formation and evolution of galaxies and black holes over a significant fraction of cosmic time. Ultra-sensitive mid- to far-IR spectroscopy will enable the first accurate measurement of both the star-formation and black-hole accretion rates in dusty galaxies over more than 90% of the age of the Universe. SPICA will enable measurements of gas-phase metallicities, densities, temperatures, radiation fields, and feedback mechanisms in large samples of distant galaxies. These observations cover a large range in mass and luminosity, from dwarf galaxies a thousand times fainter than the Milky Way to the most luminous quasars, a range necessary to understand galaxy evolution.

A second key objective of SPICA is to resolve, for the first time, the far-IR polarization, and by inference the magnetic field, of Galactic filaments, which play a critical role at the onset of the star-formation process in the assembly of star-forming condensations of dust and gas in the Milky Way. Additionally, the spectroscopic capabilities of SPICA will shed light on the nature of the turbulent gas and the way in which the compressional energy is dissipated through filament and core assembly, providing the experimental basis to advance theories of star formation within molecular clouds.

A third key objective of SPICA is the understanding of the formation and evolution of planetary systems. Planet formation is intimately linked to the evolution of the gas reservoir, which can be uniquely traced in planet-forming systems with observations of the Hydrogen deuteride (HD) molecule. SPICA will characterize the warm gas disk mass down to the gas dispersal stage and will uniquely probe multiple phases of water (warm and cold vapour, and ice) through the entire planet-forming reservoir. The study of water (which cannot be observed from Earth) throughout the evolution of planet forming systems, will also help us understand the emergence of water in the Solar System and its delivery to the Earth as it was being formed.

The scientific goals of SPICA are wide ranging and have significant overlap with the interests of the Canadian astronomical community.

2.2.5.3 Technology: The SpiCA FAR-infrared Instrument: SAFARI

By necessity, far-IR space instrumentation, be it mechanisms or metrology, must operate at cryogenic temperatures, and must do so without dissipating significant heat to stay within the well-defined, but limited, thermal budget of the spacecraft. The SpicA FAR-infrared Instrument (SAFARI) instrument has been optimized to achieve the best possible sensitivity for the primary science goal of studying galaxy evolution over cosmic time.

SAFARI has two spectroscopic capabilities: a low-resolution mode (R=300) provided by a diffraction grating and a high-resolution mode (R>3000) provided by a Fourier Transform Spectrometer (FTS). Canada is recognized as a world leader in the field of Fourier transform spectroscopy, both in academia and industry, and because of this was invited to join the team that proposed the SPICA/SAFARI instrument.

Building on its contributions to Herschel, Canada has helped to shape the development of the SAFARI instrument since 2007 and now has the unique opportunity to lead the development of one of the most critical components, the high-resolution spectrometer, a Canadian signature technology. This in turn will lead to a greater scientific return on investment for Canadian scientists. Moreover, with several far-IR space exploration projects on the road maps of the world's leading space agencies, the development of the cryogenic FTS for SAFARI will position Canadian academia and industry to become partners of choice on future missions.

2.2.5.4 Canadian Priorities

In the CASCA LRP it was noted that:

> *… the Herschel mission, in which Canada made notable contributions to both the SPIRE and HIFI instruments, is an outstanding success and has shed new light on the Universe at infrared wavelengths. However, the mission lifetime is short, 3.5 years. Current plans call for a vastly more capable mission – the Space Infrared Telescope for Cosmology and Astrophysics (SPICA). Unlike Herschel, SPICA will actively cool the mirror in the telescope and thus will achieve over a 100-fold improvement in sensitivity, enabling detailed analysis of objects that Herschel can barely detect as well as finding objects that are beyond Herschel's sensitivity limit.*
> *The LRPP gives Canadian participation in SPICA very high priority under medium-scale space projects.*

2.2.5.5 Benefits to Canadian Society

Participating in missions like Hershel and SPICA benefits Canadians at large. They serve to increase the general interest in and awareness of STEM at the local, provincial and national levels. While societal benefits of this type are difficult to measure, they foster both individual and national pride across Canada.

2.2.5.6 Summary

Building on the legacy of Canada's contributions to the Herschel Space Observatory a unique opportunity exists for Canada to develop one of the key components of the SPICA/SAFARI instrument, the high-resolution spectrometer. A sensitivity increase of two orders of magnitude over previous IR space astronomy missions commands an enormous discovery space that will not only lead to breakthroughs in key astronomical questions, but also complement discoveries made with ALMA, JWST and future large ground based telescopes. SPICA will offer the community a unique astronomical facility covering the rich 12-350 μm spectral range, capable of making deep and wide surveys to unprecedented depths in spectroscopy, photometry and polarimetry.

The SPICA project, with its international network of collaborators, provides abundant STEM training opportunities at all levels from (under)graduate to postdoctoral, in both academia and industry, on topics ranging from project management, software development, cryogenics, optics, electronics and mechanics. Moreover, other missions on the far-infrared road maps of the world's leading space agencies will require expertise in cryogenic instrumentation. By contributing to SPICA, Canada not only retains its knowledge base in the technology required for the next generation of far-IR space astronomy missions, but becomes a partner of choice with the world's leading space agencies in such missions.

2.2.6 OST: The Origins Space Telescope

2.2.6.1 Mission Concept

The OST is a large-aperture mid-to-far-IR mission being studied by NASA for the 2020 US decadal survey. The current plan is for a roughly 10-m aperture, with a complement of five instruments, giving both high and low resolution spectrographic capability, as well as imaging. OST will be an actively-cooled telescope, covering much of the IR spectrum. Cooling to below 5K yields a dramatic improvement in sensitivity compared with previous IR missions, corresponding to factors of 100 to 1000. The planned wavelength coverage of 5μm–1mm enables observations of bio-signatures in the atmospheres of transiting Earth-like planets, mid- and far-IR diagnostic lines in galaxies out to redshifts of 10, and characterisation of water from the Solar System to the interstellar medium (ISM). Fast mapping speed with hundreds or thousands of independent beams will enable 3D surveys of large areas of sky, pushing to unprecedented depths to discover and characterise diverse objects, from the most distant galaxies to the outer reaches of our Solar System.

2.2.6.2 OST Science Goals

Through a combination of surveys and open calls for proposals, OST will follow the rise of dust and metals in galaxies and the path of water across cosmic time to Earth and other habitable planets. There are four main themes driving the design of OST, ranging in scale from bodies within our own and other Solar systems to objects forming near the edge of the observable Universe.

(1) Tracing the signatures of life and the ingredients of habitable worlds

OST will trace the trail of water from interstellar clouds, to proto-planetary disks, to Earth itself facilitating understanding of the abundance and availability of water for habitable planets.

(2) Unveiling the growth of black holes and galaxies over cosmic time

OST will reveal the co-evolution of super-massive black holes and galaxies, energetic feedback, and the dynamic interstellar medium from which stars are born.

(3) Charting the rise of metals, dust, and the first galaxies

OST will trace the metal enrichment history of the Universe, probe the first cosmic sources of dust, the earliest star formation, and the birth of galaxies.

(4) Characterizing small bodies in the solar system

OST will chart the role of comets in delivering water to the early Earth, and survey thousands of ancient Trans-Neptunian Objects at distances greater than 100 AU and down to sizes of less than 10 km.

2.2.6.3 The Canadian Advantage

OST builds on Canadian expertise in the IR, particularly the ESA-led Herschel satellite. OST is effectively a more ambitious (and much further in the future) successor to the ESA/JAXA proposed mission SPICA, in which Canadians are currently discussing contributions. In the mid-IR, OST overlaps with the wavelength coverage of JWST, but will have a mapping speed around 3 times faster and a resolution about twice as good, enabling much fainter targets to be pursued. In the far-IR, OST will have unprecedented mapping speed and resolution. The science goals of OST align well with those of the “Origins” theme of previous Canadian astronomy LRPs.

2.2.7 LUVOIR: The Large UV-Optical-IR Space Telescope

The LUVOIR telescope is one of four flagship mission concepts being considered by NASA for the 2020 decadal survey, hence launching in the 2030's. LUVOIR would be a segmented mirror space telescope with around four instruments, enabling spectroscopy and imaging from the ultraviolet through the near IR. Scientifically, LUVOIR can be thought of as a giant successor to the HST, though technically it more closely resembles the JWST, albeit with silver coatings instead of gold, and with more rings of mirror segments. Two architectures are being considered: a 15 metre aperture, and a 9 metre aperture. These are limited by the size of fairings and payload mass on current and future launch vehicles.

The LUVOIR, shown in Figure 2-6, is a concept for a highly capable, multi-wavelength space observatory with ambitious science goals. This mission would enable great leaps forward in a broad range of science, from the EoR, through galaxy formation and evolution, star and planet formation, to solar system remote sensing.

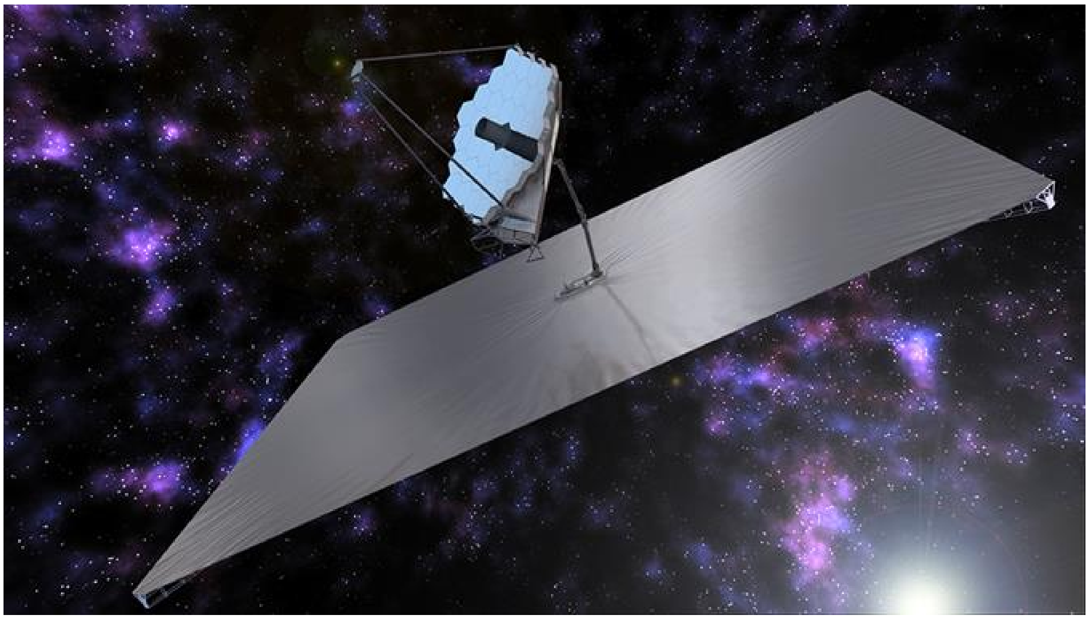

Figure 2-6 LUVOIR concept. (Source NASA/Goddard)

2.2.7.1 Instrument Development for Space

The instruments being considered for LUVOIR are: an optical/Near Infrared (NIR) coronagraph; a UV multi-object spectrograph; a high-definition imager; a UV spectro-polarimeter (contributed by Centre national d'études spatiales (CNES)); and an Optical/NIR multi-resolution spectrograph.

The marquee science for LUVOIR is directly imaging nearby Earth twins and searching their reflected spectra for signs of life. In addition to an excellent coronagraph capable of delivering 10^{-10} contrast, the exobiology objective requires a large space-based telescope because it makes for smaller inner working angles for the coronagraph and less exo-zodiacal background under the planetary point spread function. A telescope of LUVOIR’s diameter would also be remarkably good for Solar System science because it yields “mission-like” spatial resolution, e.g. LUVOIR would obtain images of Jupiter with the same spatial resolution as the recent JUNO images. That same large aperture would be extraordinarily powerful for Cosmic Origins science because it would enable one to:

(1) resolve young cluster stars anywhere in the Milky Way;

(2) resolve individual solar mass stars in the nearest elliptical galaxies (30 Mpc); and

(3) resolve galaxies to 100 parsec or better at any redshift.

2.2.7.2 The Era of Extrasolar Astrobiology

The discovery of thousands of potential and confirmed exoplanets in recent years, and the expected increases in this number with the coming launches of the Transiting Exoplanet Survey Satellite (TESS) and JWST missions, has opened the door to extrasolar astrobiology.

Extrasolar planets can only be characterized via remote sensing, primarily via disk-integrated observations. This means that we can only hope to find extrasolar life on planets where it has significantly modified the surface and/or atmosphere, as it has on Earth. Extrasolar Astrobiology is complementary to Solar System Astrobiology in three key ways:

(1) If an exoplanet exhibits signs of life, then it points to an independent genesis, as interstellar contamination is virtually impossible;

(2) If there are exoplanets that are more similar to Earth than any other world in the Solar System, so if life can only exist in closely Earth-like situations, then exoplanets are our best bet for finding extraterrestrial life; and

(3) If there are vast numbers of exoplanets, enabling comparative planetology and, eventually, comparative biology.

The capability to characterize planetary atmospheres raises the potential to search for atmospheric biosignatures. The classic example is oxygen, which is only present in Earth's atmosphere at significant levels due to the photosynthetic activities of life. Unfortunately, oxygen has only been present in sufficient quantities to be remotely detectable for 10% of Earth's history. Developing robust biosignatures that are "in-band" for planned space telescopes is an area of active research.

It is extraordinarily exciting to note that any mission capable of directly imaging an Earth analogue can characterize atmospheric biosignatures by measuring the brightness and colour variations of the planet. Colour variations of a "pale blue dot" would allow one to infer the number, albedo and location of different surface types on the planet, as well as its obliquity. In fact, such observations are the only feasible way to know whether an exoplanet has liquid surface water, the very definition of habitability according to the "habitable zone" characterization. For example, the colour variations of Earth seen from space betray not only its oceans but also its exposed continents, suggesting a planet with plate tectonics and hence long-term habitability. Such methods could even allow astronomers to identify surface biosignatures, such as the red edge of chlorophyll, though of course we can only interpret a biosignature as such if we have a thorough understanding of possible abiotic atmospheric and surface signatures.

In any event, exoplanets provide great leverage for understanding the variety of planetary atmospheric and surface conditions. Since most exoplanets that we can study are not habitable in any global way, their atmospheric and surface character must be the result of abiotic processes. Only by studying a large number of diverse worlds can we hope to put the few temperate terrestrial planets in context. For example, the growing handful of terrestrial exoplanets with well-characterized masses and radii has bulk densities consistent with Earth-like iron/silicate composition. Meanwhile, observations of polluted white dwarfs indicate that all planets form from the same basic chemical building blocks. Continued studies of "dirty dwarfs" will help pin down the universal building blocks of planets and life.

By the late 2020's, the first Extremely Large Telescopes (ELT) will come online, including the TMT in which Canada is one of the principal partners. With their large collecting area and very high spectral resolution, these ground-based telescopes may be able to tease out the atmospheric signals of nearby temperate terrestrial planets orbiting nearby red dwarfs, including atmospheric biosignatures.

However, it is likely that a flagship astrophysics mission (NASA's LUVOIR or HabEx missions) launching in the 2030s will undertake the truly transformative searches of nearby exoplanets for biosignatures.[1] Both imaging and spectroscopy provide credible approaches, with the former focusing on direct detection of liquid water, and the latter focusing on direct detection of biosignatures.

- **Direct Imaging: Establishing the Presence of Surface Liquid Water on an Exoplanet**

  There are two approaches to detecting water on a directly-imaged Earth analogue.

  (1) Water is shiny at glancing incidence, so one can detect glint (specular reflection) photometrically or polarimetrically. Directly imaging a planet at crescent phases requires a small inner working angle, necessitating a large aperture with an internal coronagraph, or a modest aperture coupled with an external starshade.

  (2) Water is dark near nadir, so one can detect oceans via rotational mapping with multi-colour photometry. This approach requires a large aperture, wide bandpasses (easier with a starshade) or multiple coronagraphs. In either case, the requirements point towards a large space telescope with a high-performance coronagraph (LUVOIR) or external starshade (HabEx).

- **Establishing the Presence of Biosignatures in an Exoplanet Atmosphere**

  For habitable planets orbiting red dwarfs, it is likely impossible to directly image the planet due to the small angular separation. However, these planets are more likely to transit their star, enabling transit and eclipse spectroscopy. The relevant biosignature molecules, notably oxygen (or ozone) and methane have absorption features in the optical and NIR. In principle, the JWST and ground-based ELTs should be able to search for biosignatures on these planets. If actual performance is not sufficiently good, then we may need a future NIR-MIR mission to search for biosignatures in the atmospheres of such planets. A LUVOIR-type mission would be an excellent fit.

  For Earth analogues orbiting Sun-like stars, transits are improbable but it is feasible to directly-image the planet in the foreseeable future. A large aperture is required in order to obtain a high signal-to-noise spectrum in a reasonable integration time. Wavelength coverage well into the NIR is needed to detect multiple atmospheric biosignatures and to rule out geochemical and photochemical false positives. A mission like LUVOIR would be capable of searching for biosignatures from the nearest Earth twins.

- **The Canadian Advantage**

  Although missions capable of establishing exoplanet habitability and detecting exoplanet bio-signatures are likely to be led by NASA due to their significant cost (>$5B), Canada is particularly well positioned to contribute instrumentation in a number of areas in which we have considerable capability and experience. Examples include: high-precision photometry (MOST, BRITE); high-precision polarimetry (Polarimètre de l'Observatoire du Mont-Mégantic (POMM)); near-IR spectroscopy (JWST/NIRISS, SpectroPolarimètre Infra-Rouge (SPIRou), Near Infra-Red Planet Searcher (NIRPS)); and direct imaging of exoplanets (GPI). Indeed, Canadian astronomers have already explored the idea of contributing the coronagraph for the WFIRST mission and there are CSA representatives on the HabEx and LUVOIR Science and Technology Definition Teams. And, of course, there is considerable and growing Canadian expertise in the characterization of exoplanet atmospheres and surfaces.

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[1] In the meantime, NASA's WFIRST mission, described earlier, is currently baselined to have a coronagraph for direct imaging of nearby exoplanets. With a primary mirror of only 2.4 metres (the same as Hubble), this mission will barely be capable of seeing the reflected light from hypothetical habitable rocky planets orbiting the nearest stars. However, it may be possible to launch a starshade to rendezvous with WFIRST at the end of the latter's primary mission. The Exo-S STDT showed that such a combination would be capable of discovering and characterizing nearby habitable rocky planets. CSA might consider supporting such a follow-on mission if Canadian interest in this concept develops. A starshade operating in concert with WFIRST provides the only credible path to exoplanet biosignatures in the next decade. A starshade allows simultaneous direct imaging over a broad wavelength range, enabling studies of exoplanet surfaces, including the mapping of oceans and vegetation.

2.2.8 HabEx: Habitable Exoplanets Imaging Mission

2.2.8.1 Mission Concept

HabEx is a 4 to 6-m UV/optical/NIR coronagraphic imaging spectrograph (R=70) space mission currently being studied by NASA for the 2020 decadal survey in Astronomy and Astrophysics. While its focus is mainly the search and characterization of planets orbiting around neighborhood Sun-like stars, it is viewed as the true successor of the HST due to it similar wavelength coverage, and larger diameter. The science reach of HabEx reach is vast, from extra-galactic astronomy and DM to circumstellar disks and exoplanets.

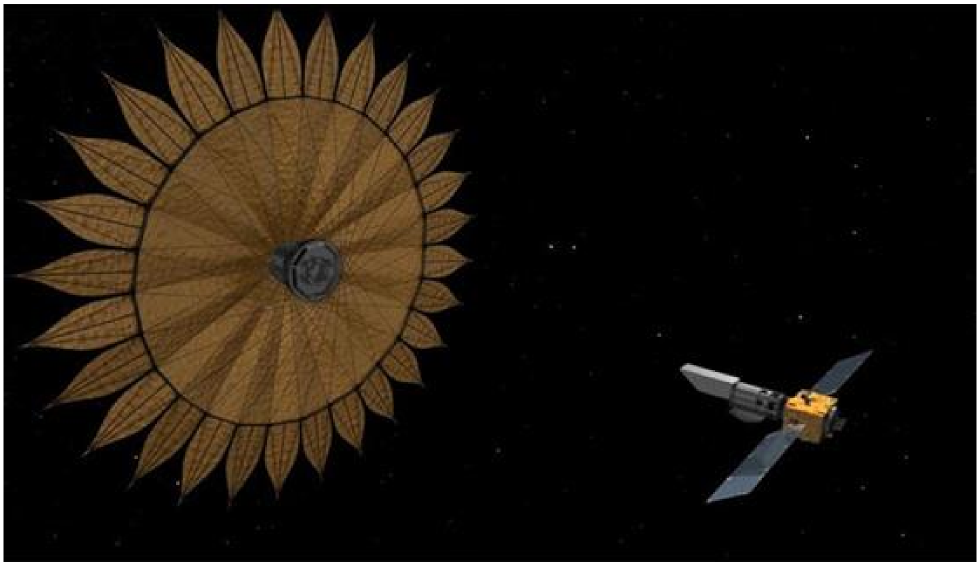


Figure 2-7 One possible HabEx concept: a star shade is flying in front of the telescope hiding the central on-axis star, while allowing the light of off-axis planets to leak to the telescope. A 10^{10} contrast is achievable with such a design. (Source NASA)

The mission architecture is still being iterated, with the interim report due in late 2017. The team is studying the science reach of various telescopes diameters (from 4 to 6m) with several internal and external (starshade) coronagraph setups (Figure 2-7).

Due to the telescope's modest size, achieving the angular resolution needed to resolve nearby planetary systems and to perform advanced habitable planet atmospheric characterization requires that the telescope be optimized for UV/visible/NIR wavelengths. This wavelength range is also filled with biomarkers (Figure 2-8) to search for life signatures, including ozone (O_3), oxygen (O_2), water vapor (H_2O), carbon dioxide (CO_2), carbon monoxide (CO), and methane (CH_4).

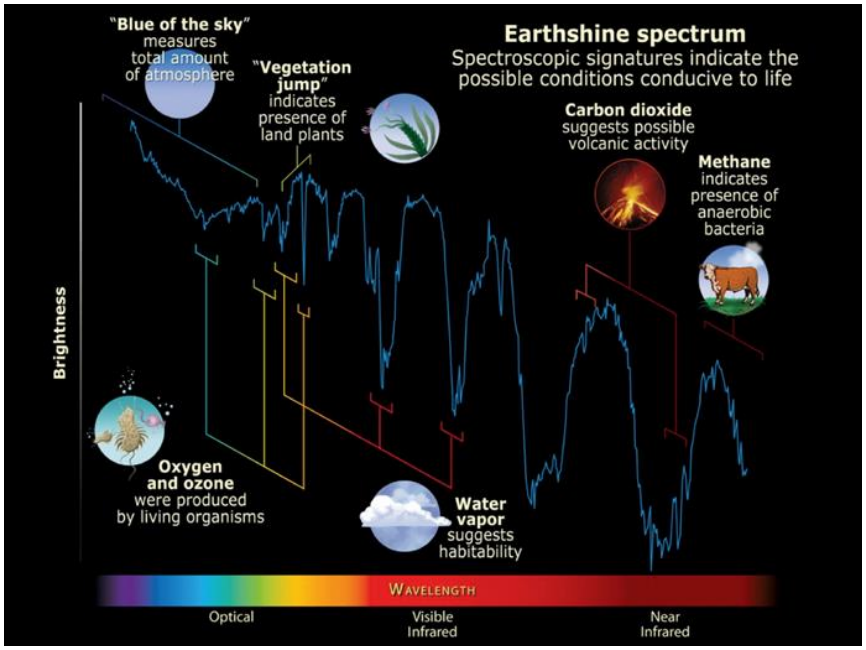


Figure 2-8 Earthshine spectrum showing the signature of Earth life from light being reflected on the moon's dark side. It is an example of the level of remote sensing that will be feasible with HabEx to search for life on distant exoplanets. (Source STScI)

2.2.8.2 High-contrast Imaging with Starshades

To reach the required 10^{-10} contrast at a few diffraction element separation to detect and characterize the faint Earth-like planet reflected light, the telescope will possibly use an external starshade to block the central on-axis star light while letting the off-axis exoplanet light to reach the telescope, or an internal coronagraph. The internal coronagraph requires parts per million levels of wavefront control and aggressive coronagraph technology to push the inner working angle close to one diffraction element to maximize the number of systems that can be imaged. The system will use a deformable mirror technology to build a dark hole where the exoplanet light can be detected (Figure 2-9).

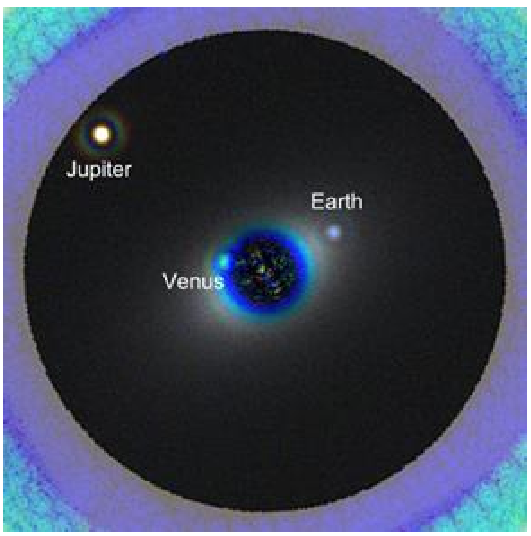


Figure 2-9 A simulated image of a Solar system-like planetary system as viewed by HabEx. A dark hole is generated, allowing the faint reflected light of exoplanet to be discovered. (Source NASA)

2.2.8.3 Spectral Characterization of Exoplanets

The telescope aperture and instrument performance are being optimized to allow low-resolution spectral characterization of nearby system. Several molecular features are expected to be detected in the reflected light spectrum (see Figure 2-10).

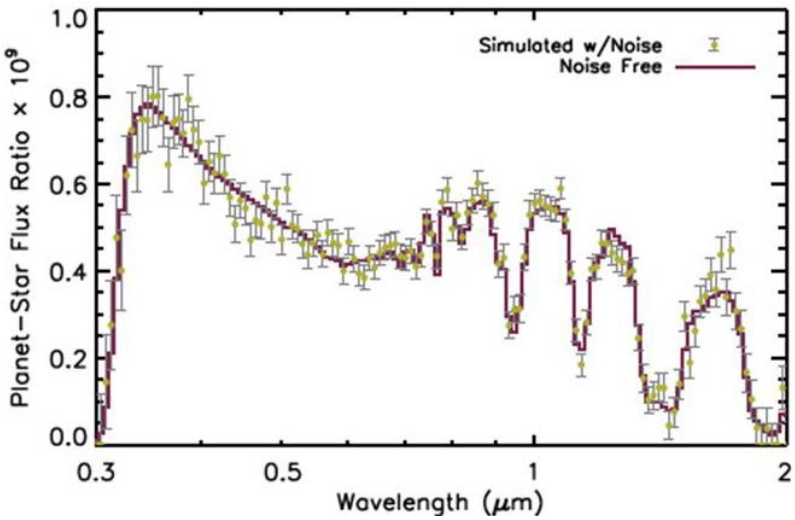


Figure 2-10 ([1]) Simulated spectrum of an Earth analogue around Tau Ceti (a G8V star located at 3.6 pc), as observed with a 5-m telescope providing a 10^{-9} raw contrast outside a 2λ/D inner working angle.

Beside Earth-like planets, HabEx is also expected to find and characterize a wide range of planet atmospheres, from Earth-like to water worlds, Neptune-like and gas giants such as Jupiter.

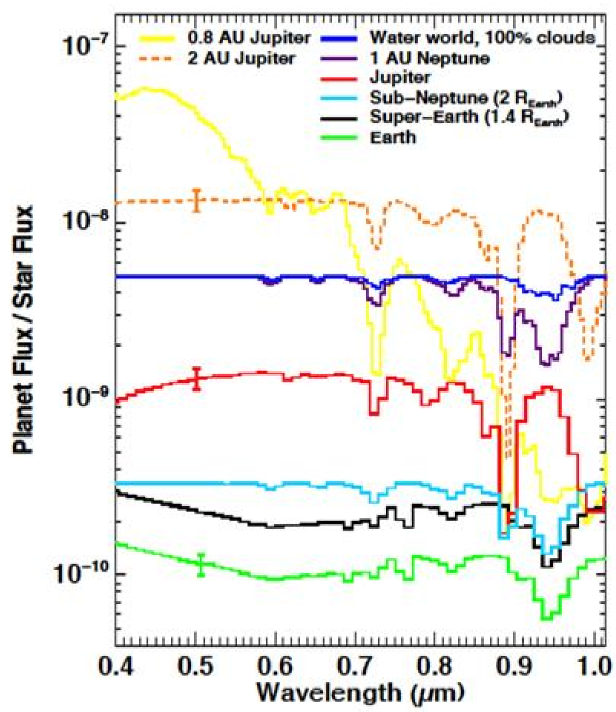


Figure 2-11 ([2]) Differences and similarities in brightness and spectral features for a variety of exoplanet types. Optical reflectance spectra of a diverse suite of exoplanets are shown without added noise.

2.2.8.4 The Canadian Advantage

The HabEx mission would offer Canadian astronomers a unique state-of-the-art platform in the UV/optical/NIR optical window to perform ground-breaking science (see Table 2-3), while being part of the first flagship space mission that is expected to characterize the atmosphere of a large amount of nearby planetary systems, including planets similar to Earth, around Sun-like stars.

2.2.8.5 Summary

Table 2-3 shows possible general astrophysics themes to be pursued by HabEx and corresponding instrumental requirements (all notional).

Table 2-3 Possible general astrophysics themes to be pursued by HabEx and corresponding instrumental requirements

Science Driver	Observation	Wavelength	Spatial R	Spectral R	Field of view
Local Hubble Constant	Image Cepheid in SN Ia host galaxies	Optical- NIR	Diffraction Limited	Low	3' x 3'
Galaxy Leakiness and Reionization	UV imaging of galaxies (LyC photons escape fraction)	UV, preferably down to LyC at 91 nm	10-20 mas	R ~ 1000-3000	few arcmin
Cosmic Baryon Cycle	UV imaging & spectroscopy of absorption lines in background QSOs	Imaging down to 115nm Spectroscopy down to 91nm	10-20 mas	R ~ 40000	3' x 3'
Massive Stars /Feedback	UV imaging & spectroscopy in the MW and nearby galaxies	110-1000nm imaging 120-160 nm spectroscopy	< 40 mas	R ~ 10000	3' x 3'
Stellar Archaeology	Resolved photometry of individual stars in nearby galaxies	Optical (500-1000nm)	Diffraction Limited	Low	3' x 3'
Dark Matter	Photometry and astrometric proper motion of stars in Local Group dwarf galaxies	Optical (500-1000nm)	Diffraction Limited	Low	TBD

2.2.9 Recommendations

The comprehensive contributions of Canadian scientists and industry to several missions over past decades means that Canada now has the expertise to lead a mid-scale (totaling of order $500M, spread over a decade) space-science mission where we welcome IPs to join a Canadian-led project (rather than the other way around). The total cost to Canada is likely to be comparable to that of our share of JWST. The project would stimulate our aerospace industry, retain the best scientists and engineers, and inspire a new generation of young Canadians and the general public. The CASTOR mission is a strong prospect for such a Canadian "flagship" mission.

At the same time as Canada grows its capabilities by leading a mid-scale mission, we should not lose sight of the fact that leadership in a mission like CASTOR only makes sense as a component of a broader space astronomy program. Participation at a lower level in international missions led by other agencies is also an essential component of the ecosystem. Partnerships in such missions provide continuity in engagement, which universities and industrial partners require for technical expertise to be retained between flagship missions. When mission planning takes decades, retention of this expertise is critical. Once lost, highly skilled human capital operating at the top international level is not easily required.

The internationally-acknowledged excellence of Canadian astrophysics is based largely on a partnership of top-echelon engineering and academic talent that we should do our utmost to retain. For example, it is almost unimaginable that after having striven for decades to develop world-class expertise in exoplanet research, and having developed key technologies that have driven the subject forward in a myriad number of ways, Canada would now choose to turn its back on participation in key exoplanet missions at just the time when humanity is set to explore the habitability of nearby worlds around the solar neighborhood. Similarly, the recognised Canadian expertise in cosmology means that we should be endeavouring to be involved in the most exciting new projects to probe the nature of the Dark Energy and the first instants in the history of the Universe. In these subjects, as with others noted in this document, Canada has reached a point where it has an historic opportunity to make a scientific mark on a subject that is of tremendous interest to almost all people.

2.2.9.1 Conclusions

We conclude this report by emphasizing that Canada's aspirations in Space Astronomy are large, but our goals are achievable. Our resources are currently inadequate, but our participation in JWST shows that the resources needed are well within our nation's capacity. Ultimate success requires careful planning with an eye toward sustainability. Therefore, at the heart of the model for developing Canadian space astronomy should be a process that allows for sustainable investments in space astronomy and coordination with CSA's industrial and university-based partners. A succession of competitive calls for proposals, arranged with a cadence that encompasses a planning horizon of about ten years duration, would best grow Canadian expertise in space science and technology.

Such long-term planning would allow Canadian participation in several international missions at different stages under development, along with leadership of a mid-scale mission. Participation in all these activities should be chosen competitively. This process would fuel innovation and cultivate a broad and deep space industry. Funding should be divided nearly equally into small projects and missions, medium missions and large missions to develop depth and continuity in the sector. This framework will stimulate vigorous interactions between scientists and aerospace companies throughout Canada by generating a series of competitions for missions; each call would have several levels of competitive assessment and development, cultivating a broad range of collaborations and technologies and creating a robust ecosystem for space astronomy missions in Canada.

2.3 High-Energy Astrophysics (HEA)

Community Report from the Space Astronomy Topical Team on High-Energy Astrophysics

Table 2-4 Space Astronomy - High-Energy Astrophysics Topical Team

(Student and postdoc names are shown in italics)

Name	Affiliation
Luigi Gallo (Chair)	Saint Mary's University
Arif Babul	University of Victoria
Kirsten Bonson	*Saint Mary's University*
Ilaria Caiazzo	*University of British Columbia*
Daniel Capellupo	*McGill University*
Andrew Cumming	McGill University
Stephane Gagnon	Neptec Design Group
Sarah Gallagher (Co-chair)	Western University
Adam Gonzalez	*Saint Mary's University*
Frederic J. Grandmont	ABB
Daryl Haggard	McGill University
Pat Hall	York University
Craig Heinke (Co-chair)	University of Alberta
Julie Hlavacek-Larrondo (Co-chair)	Université de Montréal
Jeremy Heyl (Co-chair)	University of British Columbia
John Hutchings	National Research Council
Natasha Ivanova	University of Alberta
Victoria Kaspi	McGill University
Denis Leahy	University of Calgary
Brian McNamara	University of Waterloo
Mar Mezcua	*Université de Montréal*
Anthony Moffat	Université de Montréal
Dae-Sik Moon	University of Toronto
Rachid Ouyed	University of Calgary
Neil Rowlands	Honeywell
Samar Safi-Harb (Co-Chair)	University of Manitoba
Gregory Sivakoff	University of Alberta
Ingrid Stairs	University of British Columbia
Neven Vulic	*Western University*
Dan Wilkins	*Saint Mary's University*

2.3.1 Introduction to High-Energy Astrophysics in Canada

High-energy astrophysics (HEA), referring specifically to X-ray and gamma-ray astronomy, must normally be carried out from space. The field of HEA has experienced substantial growth in Canada over the past decade. Since the early 2000s we have seen over a dozen faculty hires (including into prestigious Chair positions), the formation of HEA research groups, and the contribution at a national level of hardware and expertise to the international X-ray missions Hitomi and ASTROSAT.

Our growth and activities have brought the Canadian HEA community to world-class levels and we are playing leadership roles in HEA efforts across the globe. We have led hardware development on HEA spacecraft; are actively involved in future mission development (e.g. Athena, Arcus, Neutron star Interior Composition Explorer (NICER)); and are driving legacy projects with current X-ray observatories (e.g. XMM-Newton and Chandra). Our students and postdoctoral researchers (Highly Qualified Personnel (HQP)) are achieving great success. Our HQP have carried out work in instrument laboratories at international space agencies and with Canadian industrial partners; won accolades (e.g. the CASCA's Plaskett medal) and fellowships (e.g. Natural Sciences and Engineering Research Council (NSERC) Canada Graduate Scholarships and CITA-National Postdoctoral Fellowships) for their research; and are finding career positions in academia and industry.

The community is established at the forefront of scientific discovery and actively engaged in tackling the most compelling problems.

(1) Accretion physics in the inner regions of compact objects

Some of the most energetic phenomena seen in the Universe like gamma-ray bursts, active galaxies, and X-ray binaries are powered by accretion. However, aside from general global properties, very little is known of the mechanism that transports material to the central compact object and how gravitational potential energy is extracted.

(2) Feedback mechanisms on all scales

Stellar winds, supernova explosions, and AGN can eject copious energy into their surroundings, chemically enrich the environment, and accelerate cosmic rays (CR) to near-relativistic velocities. These processes can trigger or disrupt star formation on galactic scales or heat the intracluster medium on much larger cluster scales. How the feedback process works in different systems is important for explaining the evolution of stars and galaxies. In conjunction with understanding how the feedback mechanism works, we are striving to understand how the processes are manifested in the surroundings and how the environment responds to the deposition of energy by black holes and supernovae.

(3) Demographics of black holes

All large galaxies harbour a supermassive black hole at their centres. The growth of the black hole and its host galaxy are intimately related through feedback processes, but exactly how they co-evolve is uncertain. To understand the galaxy-black hole co-evolution, we need to have an accurate census of black holes. The penetrating ability of X-rays enables them to reveal enshrouded black holes that are invisible at other wavelengths. X-rays potentially reveal the black holes that are deeply enshrouded in dust and gas, which are aggressively growing, but emitting little at other wavelengths.

(4) Physics of dense matter and extreme magnetic fields

Compact objects (white dwarfs, neutron stars and black holes) are the most extreme objects in the Universe. Consequently, they stress our understanding of Nature, testing our theories and indicating ways to extend them. Neutron stars provide laboratories to explore material at the highest densities and in extreme conditions of temperature, magnetic field, and pressure. White dwarfs provide precision tests of weak interactions, gravity and dark matter in regimes impossible to explore otherwise. And black holes provide the purest tests of general relativity, the theory of dynamic spacetime.

2.3.1.1 Prioritised List of Objectives

- HEA-01 - Accretion physics in the inner regions of compact objects
- HEA-02 - Feedback Mechanisms on all Scales
- HEA-03 - Demographics of Black Holes
- HEA-04 - Physics of dense matter and extreme magnetic fields

2.3.2 *HEA-01 - Accretion physics in the inner regions of compact objects*

Accretion is prevalent across most fields of astrophysics from star and planet formation to gamma-ray bursts. However, the mechanics that power the most energetic processes in the Universe remain largely unknown.

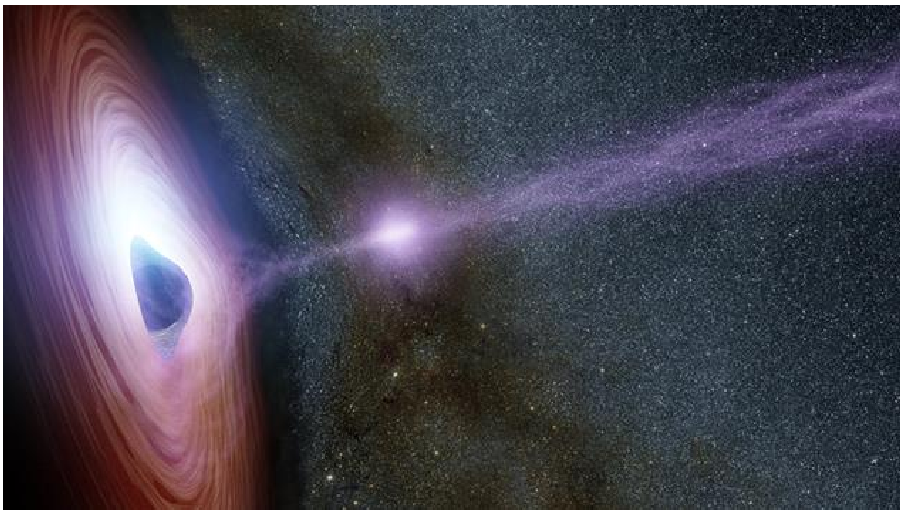


Figure 2-12 A supermassive black hole is depicted in this artist's conception surrounded by a swirling disc of material falling onto it. ([3])

In stellar and supermassive black holes, the primary hard X-ray photons are generated in a corona of electrons that illuminates the accretion disc. This primary emission is reprocessed and backscattered in the accretion disc producing the so-called reflection spectrum, which contains information on the composition of the disc, its dynamics, and essential black hole properties like mass and spin. The reflection spectrum can also be used to unravel the behaviour and geometry of the X-ray corona itself.

Stellar mass black holes and neutron stars can accrete matter from a nearby companion through stellar winds (Bondi-Hoyle accretion) or directly from the surface of the companion (Roche-lobe overflow). Both processes can lead to the formation of an accretion disc that transports mass onto the compact object. The strong magnetic fields associated with neutron stars can funnel the accreted material directly onto the magnetic poles.

2.3.2.1 Preparatory Research

Specific investigations pursued:

(1) What happens within the inner light hour of the accretion disc around AGN?

(2) What is the structure of the X-ray emitting region of the accretion disc?

(3) What powers the corona? What drives X-ray weak and strong sources?

2.3.2.2 Investigations and Data Analysis

Canadian researchers across the country are leading investigations on the workings of the inner accretion disc around black holes. Using data from current major observatories (e.g. XMM-Newton, Nuclear Spectroscopic Telescope Array (NuSTAR), and Chandra), researchers are actively examining the nature of the corona and its link to the accretion disc. Recent work identifies multiple components in the coronae of some AGN, and measures the spin of spinning black holes. Computer simulations are used to validate observational results and build models that predict behavior that can be observed with future X-ray instruments.

Canadian researchers also lend expertise to International Science Working Groups of several past and future X-ray missions (e.g. Astro-H, Athena, Arcus, HEX-P). Computer simulations derived by Canadian teams are used to drive science requirements for future missions.

2.3.2.3 Instruments Needed

X-ray spectral and timing behaviours reveal the corona and accretion disc properties:

- Broadband (0.5-40+ keV, X-ray) spectral coverage and large effective area are required to accurately characterize the X-ray spectrum. Together, these enable observations of the spectral cutoff that reveals the corona temperature in accreting black holes, and identifications of cyclotron absorption lines that measure the magnetic field strength in high-mass X-ray binaries.
- Spectral modelling of the iron K-alpha line profile requires broadband spectral coverage and high effective area. Accurate modelling discloses the geometry of the corona, disk composition, and even black hole spin.
- Measuring iron line variations on short timescales will elucidate the origin of quasi-periodic oscillations that are seen around neutron stars and stellar-mass black holes. High effective area, fast timing resolution, and good spectral resolution are required for this pursuit.
- The transitions between accretion- and rotation-powered regimes require high timing resolution and large effective area.

2.3.3 *HEA-02 - Feedback Mechanisms on all Scales*

Black holes – objects so compact that their gravitational pull prevents everything from escaping, even light - have long been the focus of scientific scrutiny. However, only recently have scientists realized their cosmological importance, and the undeniable role they play in shaping the properties of galaxies.

When the Chandra X-ray Observatory was launched in 1999, it revealed that the hot gas in clusters of galaxies is not uniform, but often contains regions of depleted gas that resemble cavities (or “bubbles”). These X-ray cavities are gargantuan pits, carved out by the supersonic jets of the black hole in the central dominant galaxies. More precisely, as the central supermassive black hole forms jets, these propagate through the intracluster gas (traced by the X-rays) and push it away to create these enormous structures.

While the discovery of these structures demonstrated that black holes can generate extremely energetic outflows in galaxies, groups and clusters, energetic enough to completely disrupt the host galaxies, we still do not understand how the surrounding medium responds to these outflows, and more generally how black holes and starburst driven outflows are generated.

Figure 2-13 Shown is a multi-wavelength image of the Perseus cluster of galaxies. The X-ray (blue) is an accumulation of more than 350 hours of Chandra observations and the radio (pink) is a low-frequency view of the powerful outflows being generated by the supermassive black hole in the central galaxy, NGC 1275. This figure illustrates the tremendous power black holes can have on their surrounding. ([4])

Supernovae (SNe) are the main sources for the chemical enrichment of the Universe, the acceleration of CRs to extreme energies, and the formation of some of the most exotic and magnetic objects in the Universe. Type Ia SNe have also been used as standard candles for cosmology, which led to the 2011 Nobel Prize for the discovery of the accelerating Universe.

It is well known that most of the heavy elements are created during the nucleosynthetic processes of massive (>8 solar masses) stars that are the progenitors of core-collapse supernova explosions. However, the details of these important processes and how elements are created and dispersed into the interstellar medium remain unknown to date, due largely to the lack of reliable nucleosynthesis models and systematic and dedicated studies of SN progenitors.

Massive stars will spend 90% of their lifetimes on the Main Sequence. Despite being relatively rare among the population of stars, massive stars have extreme outputs in energetic radiation and winds, and thus dominate the ecology of the Universe. Energetic processes originating below the stellar surface in massive stars can create hot spots that glow in X-rays and drive clumps and shocks that propagate outward in hot, energetic stellar winds.

Main-Sequence massive stars above an initial mass of 20 solar masses have ever higher luminosities, which blow progressively stronger, faster winds. Because of these winds and their structures, hot massive stars manifest themselves as significant high-energy sources. Important scientific questions on the origin and nature of these winds, and the effect of this mass loss on the evolution of massive stars (for instance, determining whether some stars collapse to form neutron stars or black holes), remain to be answered with future X-ray observations.

Furthermore, the origin of high-energy CRs remains a mystery, and a main driver for high-energy (hard X-ray and gamma-ray) missions. Supernova remnants (SNRs) have long been thought to be the primary source of CR acceleration up to the "knee" of the CR spectrum (3×10^{15} eV). While the non-thermal radio emission from SNR shells indicates the presence of gigaelectronvolt (GeV) electrons, the presence of tera electron volts (TeV) electrons was first demonstrated with X-ray observations with Advanced Satellite for Cosmology and Astrophysics (ASCA) of the young Galactic supernova, SN 1006. Recent gamma-ray observations, particularly in the very high-energy TeV band, have opened a new window to address this question and to directly image sites for TeV emission. However, uncertainties remain as to the maximum energy of CRs accelerated at SN shocks (with respect to the "knee" of the CR spectrum) and whether this emission is dominated by leptonic or hadronic processes.

2.3.3.1 Preparatory Research

Specific investigations pursued:

(1) What drives outflows in AGN?

(2) What are the properties (density, velocity, geometry, kinetic luminosity) of outflows in active galaxies?

(3) What are the dynamics of groups and clusters of galaxies on nuclear and galaxy scales?
How do AGN-associated accretion/outflows in the nuclear regions connect to kpc scales and beyond?

(4) When and how do starburst winds dominate over black hole outflows in governing the growth of galaxies?

(5) What is the impact of winds from galaxies on their groups or cluster halos?

(6) What is the life cycle, or heating and cooling, of hot atmospheres of galaxies over cosmic time?

(7) How do supernovae energize and enrich the environment with the elements essential for life?
How do massive stars (that eventually explode in supernovae) lose mass and interact with their environment and what role do their magnetic fields play?

(8) What is the origin of the high-energy cosmic rays pervading our Galaxy and the Universe?
What is the dominant acceleration mechanism in supernova shocks?

2.3.3.2 Investigations and Data Analysis

Canada is playing a vital role in our understanding of supermassive black holes and the role they play in shaping galaxies, groups and clusters. Using state-of-the-art observations, from the largest observatories (e.g. Chandra, Hubble, XMM-Newton, NuStar), scientists have undertaken several studies that have helped us understand how black holes drive jets, and how these jets interact with the surrounding hot halos. In addition, several Canadian researchers have played a direct role in leading the science for the Hitomi mission and its published white papers, and interpreting and analyzing Hitomi data of the Perseus cluster and SN remnants, with some transformative results published in Nature, despite the short time span of the mission. Researchers across the country are also involved in the development of several upcoming space missions, including Athena.

Canadian researchers are leading studies of SNRs and their connection to SN progenitors, the Galactic magnetic field and high-energy cosmic rays. Methods used rely on observations and theory, using multi-wavelength studies (radio, X-ray and gamma-rays), sophisticated 3D numerical simulations (on local clusters and Compute Canada supercomputers), and the development of the X-ray and gamma-ray catalogue of SNRs which has become a reference in the field heavily used by the community worldwide.

Current X-ray observations of SNRs (e.g. with Chandra, XMM-Newton, NuSTAR) by Canadian researchers are shedding light on the diversity of SN progenitors and associated compact objects, while also motivating new theoretical work on nucleosynthesis models and explosion mechanisms. Predictions of the effect of efficient cosmic ray acceleration at SN shocks and the magnetic field will be tested with future missions such as Athena, in synergy with observations across the electromagnetic spectrum.

2.3.3.3 Instrument Needed

- Broadband spectral coverage and high effective area are required to accurately model all spectral components.
- High spectral resolution between 0.3 to 10 keV is required to identify outflow features and accurately measure ionisation states and velocities.
- Excellent spectral resolution with non-dispersive spectrometers (e.g. calorimeters), combined with good angular resolution and sensitivity, is needed to accurately measure abundances and velocities in SN and their remnants, and compare to numerical simulations and 3D mapping of ejecta.
- A large X-ray telescope with Chandra-like or better collecting area, combined with excellent spectral resolution, will be needed to probe the workings of hot massive stars' plasma winds. High spatial resolution (1-10 arcseconds) will be needed to probe shock regions and colliding winds in star clusters and binaries.
- Hard X-ray coverage (above 10 keV) combined with modest angular resolution to map cosmic ray acceleration sites, in synergy with radio and gamma-ray observations.
- X-ray polarimetry to map the magnetic fields in pulsar wind nebulae and SNRs, in connection to the Galactic magnetic field and particle acceleration mechanisms. X-ray polarimetry, combined with monitoring capabilities in the 1-50 keV range, potentially provides a new way to study particle acceleration in magnetically confined massive stars' winds (usually probed with spectroscopy and photometry in the optical and UV).
- High angular resolution and large FOV to measure cluster properties out to large radii.

2.3.4 HEA-03 - Demographics of Black Holes

Galaxy evolution is influenced by the activity of the central black hole. To understand this symbiosis requires knowledge of AGN populations at high redshift and in obscured systems. We need to investigate how supermassive black holes are built up so rapidly, very early in the Universe. Identifying the seeds of these black holes at high redshift, and determining the processes by which they grow, will reveal the synergy between black hole growth and galaxy evolution.

2.3.4.1 Preparatory Research

Specific investigations pursued:

(1) What is the origin and evolution of supermassive black holes and how do these influence the physics in groups and clusters at early epochs?

(2) What is the relationship of binary mergers and gas accretion to the history of the growth of supermassive black holes over cosmic time? What is the black hole spin distribution in AGN?

(3) What is the duty cycle of AGN activity over its lifetime?

(4) What are the seeds of supermassive black holes?

2.3.4.2 Investigations and Data Analysis

Canada is playing a leading role in deep and wide extragalactic surveys at all wavelengths from radio to UV. The data from X-ray surveys will complement these ongoing studies. As data from JWST and Euclid become available, the data from deep and wide X-ray surveys will become necessary to keep Canada at the forefront.

2.3.4.3 Instrument Needed

- A wide field and large effective area over a broad energy range to identify faint sources at high redshift.
- Broadband spectral-imaging capabilities above 10 keV to identify highly obscured sources and resolve the cosmic X-ray background.
- Moderate spectral resolution and large effective area to accurately model iron profiles and measure black hole spin.

2.3.5 HEA-04 - Physics of dense matter and extreme magnetic fields

Neutron stars probe our understanding of the fundamental processes in the Universe in the most extreme conditions. Their interiors are governed by the strong interaction in a regime inaccessible to experiments on Earth. Their cooling is dominated initially by the emission of neutrinos (weak interactions) again in an inaccessible regime. Outside the star, the radiation passes through magnetic fields billions of times stronger than those which can be produced on Earth. These magnetic fields fuel some of the largest repeating explosions in the Universe, so powerful that they can turn night into day for the Earth’s ionosphere from across the galaxy. Of course, these objects also harbour strong gravitational fields. The escape velocity from their surfaces can exceed half of the speed of light.

A key goal of modern physics is to understand the nature of the strong interactions at high densities. A key question is whether there exist “exotic” phases of matter at such high densities, and the interior of neutron stars is the only place to examine this regime in nature. One can probe the details of the high-density regions through measurements of the radii and masses of neutron stars. The radii depend most strongly on the equation of state just above nuclear density, while the maximum mass depends on the equation of state at much higher densities, so observations of a variety of neutron stars could yield unprecedented probes of this regime. Although observations of radio pulsars can yield precise estimates of neutron star masses, the X-ray emission from the surfaces of neutron stars contain the most direct data on the radii of neutron stars.

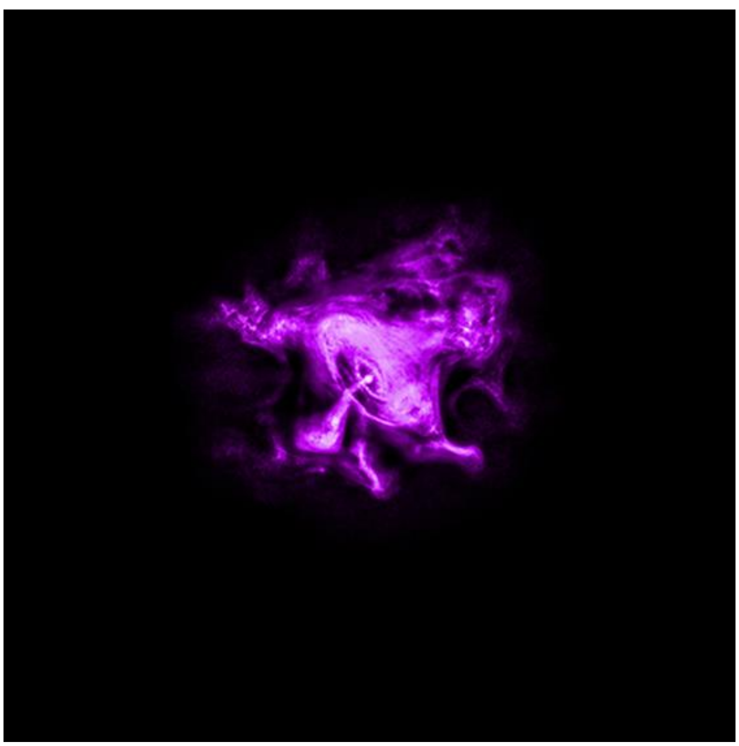


Figure 2-14 Chandra image of the Crab nebula reveal the structure and behavior of the high-energy particles being spewed from the Crab's central pulsar. ([5])

X-ray observations of neutron stars lead to several avenues to constrain the properties of dense matter. The most direct avenue uses a model of the neutron star atmosphere to constrain the radius of a neutron star at a known distance, from the measurements of the spectrum and total flux from the surface. The best objects for this approach are nearby isolated neutron stars, and accreting neutron stars in globular clusters, where we have an independent estimate of the distance. Of course, the details matter, and to constrain systematic errors both detailed emission models and comprehensive spectroscopic data are required.

A second, complementary, technique is to use the observed X-ray light-curves of rapidly rotating neutron stars to constrain:

a) the ratio of the mass and radius of the neutron star, which controls the amplitude of the pulsations; and

b) the radius of the neutron star, which for a (measured) spin frequency sets the phase lead and change in amplitude as a function of photon energy.

Such investigations require a large collecting area, high time resolution, and moderate energy resolution.

The surfaces of neutron stars harbour the strongest magnetic fields that we have measured so far in the Universe. These strong magnetic fields mold the materials at the surface (the atmosphere), provide energy for bursts and quiescent emission, transform the radiation propagating through them, and in principle can distort the star. High-resolution spectra of the surface emission from neutron stars contain signatures of how the magnetic fields alter the material that make up the neutron star. At the most basic level, magnetic fields can cause the lowest-density layers of neutron stars to be solid rather than gaseous, despite the very high temperatures. The expected emissions from these two possibilities are of course quite different. The dynamics of the magnetic fields outside of the neutron star dominate the burst emission from magnetars. High time resolution observations with large collecting area of magnetars in outburst would provide an amazing probe of magnetic reconnection in this exotic, relativistic regime.

The magnetic fields surrounding neutron stars are so strong that they even affect how light propagates through them. In particular, the polarization fraction of the radiation is expected to be dramatically larger due to the interaction of the light with the magnetic field. Here X-ray polarimetry can probe the birefringence of the quantum electrodynamic (QED) vacuum. It can also provide an independent measurement of the equation of state within the neutron star, using vacuum birefringence as a microscope to probe the thinnest upper layers of the neutron-star atmosphere and determine the surface gravity of the star. Finally, if the magnetic fields are sufficiently strong within the neutron star to distort it, a comprehensive timing campaign that might be possible with a sensitive all-sky monitor could reveal these distortions through the modulation of the spin by free precession of the star. Furthermore, a deep X-ray survey of the full sky with good spectral and angular resolution would also discover many more interesting neutron stars in the Galaxy.

Multi-wavelength observations of the remnants of SN have revealed a growing zoo of compact objects and associated nebulae, hinting at different birth properties of pulsars and the environment in which they evolve. For example, X-ray and gamma-ray observations revealed the presence of magnetars (believed to be the strongest magnets in the Universe), some of which are hosted in SNRs. Magnetars have been suggested to power some Gamma-ray Bursts. We still do not know what type of explosion makes these extreme objects and how they are connected to some of the most energetic extragalactic events (including the Fast Radio Bursts). On the other hand, some SNR observations show that some neutron stars appear to have much lower magnetic fields (by orders of magnitude in comparison to either magnetars or Crab-like pulsars), which may be connected to the nature of the SN that created them. Other SNRs appear to be dominated by non-thermal X-ray emission, unlike what’s expected from a SN explosion. Addressing this diversity can be done by probing the SN progenitors.

2.3.5.1 Preparatory Research

Specific investigations pursued:

(1) What is the equation of state for neutron star material and how can we probe the interiors of neutron stars?

(2) What are the properties of material and light in strong magnetic fields?

(3) What is the magnetic field structure in pulsar wind nebulae and SNRs that accelerate cosmic rays?

(4) What causes the diversity or zoo of compact objects observed in SNRs?

2.3.5.2 Investigations and Data Analysis

Canadian researchers across the country are leading investigations on neutron stars and the physics of the extreme associated with these fascinating objects (including their super-strong magnetic fields and relativistic winds). Using data from current major observatories (e.g. XMM-Newton, NuSTAR, and Chandra), researchers are actively examining the diversity of these objects, from accretion-powered neutron stars, to isolated pulsars displaying a wide range of magnetic fields and spin properties. Computer simulations are used to validate observational results and build models that predict behavior that can be observed with future X-ray instruments.

Canadian researchers also lend expertise to International Science Working Groups of several future X-ray missions (e.g. Imaging X-ray Polarimetry Explorer (IXPE), X-ray Imaging Polarimetry Explorer (XIPE), enhanced X-ray Timing and Polarimetry (eXTP), NICER, Lynx, X-Caliber, Athena) that especially probe the extreme physics of neutron stars. Computer simulations derived by Canadian teams are used to drive science requirements for future missions.

2.3.5.3 Instrument Needed

- High spectral resolution between 0.3 to 10 keV with high sensitivity to measure the spectra of neutron stars in principle as a function of rotational phase.
- Sensitive wide-field X-ray monitor for timing studies, to discover new sources and identify when sources go into outburst.
- Wide-field and large effective area at low energies to identify and build samples of cooling neutron stars.
- Hard X-ray timing with microsecond time resolution and effective area to characterise oscillations in neutron stars.
- Polarimetry capabilities to measure linearly polarised radiation spectra in neutron stars, pulsar wind nebulae and SNRs.
- High-sensitivity and spectral resolution (0.1 to 10 keV) to detect thermal X-ray emission from the synchrotron dominated SNR sources, to infer the SN progenitor mass, and to search for cyclotron features that would directly probe their associated neutron stars' magnetic field.

2.3.6 HEA - Missions and Payloads

2.3.6.1 Polarimetry Missions

Polarization occurs when the oscillations of the electromagnetic (EM) field are aligned. The measurement of polarized EM radiation discloses information on the presence of dust, the nature of magnetic fields and various scattering process. However, the detection of polarized X-rays is difficult and has been limited to only two astronomical objects. Future instruments will use a gas-filled chamber that tracks the direction of the liberated electron when the gas atoms are ionized by incoming X-rays.

Polarimetry concepts that are being studied include IXPE, XIPE, Polarization Spectroscopic Telescope Array (PolSTAR), Polarimeter for Relativistic Astrophysical X-ray Sources (PRAXyS), and eXTP. Potential areas of contribution are discussed in detail in Section 2.3.7, but include: metrology, data archiving, testing facilities, and general scientific expertise. The HEA community considers a polarization mission to have high scientific merit in the study of compact objects. The overall level of interest in the Canadian community is medium.

2.3.6.2 High-spectral Resolution Missions

Achieving high-spectral resolution in X-ray astronomy is challenging because of the low brightness of most astronomical sources and the difficulty to diffract high-energy photons. New missions incorporate large effective areas with diffraction gratings or non-dispersive spectrometers (e.g. calorimeters) to overcome these difficulties. The combination of large collecting area and high-sensitivity calorimetry is one of the drivers for the future Athena mission.

Mission concepts that focus on high-spectral resolution are X-ray Astronomy Recovery Mission (XARM) (Hitomi-2), Arcus, Athena, and Lynx. Potential areas of contribution are discussed in detail in Section 2.3.7, but include: metrology, data archiving, testing facilities, and general scientific expertise. In addition, these missions also present the potential to develop other areas of expertise as described in Section 2.3.7. Depending on the mission in question, the overall level of interest in the Canadian community for high-spectral resolution missions is either medium or high.

2.3.6.3 Broadband Imaging Spectroscopy Missions

Typical grazing incidence optics are most effective for focusing X-rays with energy below 10 keV. However, most astronomical X-ray processes emit over a much broader energy range and are variable. It is desirable to simultaneously observe an energy range that is as broad as possible. To focus at energies greater than 10 keV requires, in addition to grazing incidence optics, multi-layer mirror coatings to enhance reflectivity of high-energy X-ray photons. Such technologies were successfully demonstrated on NuSTAR and Hitomi (before its untimely failure) to focus X-rays up to about 70 keV. Future missions aim to enhance the effective area and energy range to which high-energy X-rays can be focused.

Mission concepts that examine broadband imaging spectroscopy include Focusing On Relativistic universe and Cosmic Evolution (FORCE) and High-Energy X-ray Probe (HEX-P). Potential areas of contribution are discussed in detail in Section 2.3.7, but include: metrology, data archiving, testing facilities, and general scientific expertise. In addition, these missions also present the potential to develop other areas of expertise as described in Section 2.3.7. The overall level of interest in the Canadian community for broadband spectroscopy and imaging missions is medium.

2.3.6.4 X-ray Astronomy Recovery Mission (XARM)

JAXA and NASA are working on a new mission to replace Hitomi (Astro-H), which was lost 6-weeks after launch. The CSA and Canadian industry (Neptec Design Group) produced the Canadian Astro-H Metrology System (CAMS) for Hitomi. The CAMS measured distortions in the extendible optical bench that would have affected X-ray data quality. The in-flight performance of the alignment system was significantly above requirements.

The XARM is highly ranked by JAXA and NASA. The Hitomi observations of the Perseus cluster demonstrated how X-ray spectroscopy with calorimeters was transformational. XARM is on an accelerated timescale and set to launch in 2021.

XARM will include two instruments: a calorimeter and a wide-field Charge Coupled Device (CCD) camera. Unfortunately, the new mission will not include the extendible bench and will not require a CAMS. There is the possibility to contribute to the mission by providing access to Canadian facilities like the Canadian Light Source for calibration purposes (Section 2.3.7).

2.3.6.5 The Athena Mission

The LRP 2010 recommendation regarding Athena, which was echoed by MTR 2015, reads:

> *The LRPP strongly recommends Canadian R&D involvement in the [Athena] as its number 1 medium-scale space priority. This is because of its excellent foreseen scientific capabilities that will be a superb match for the expertise of the Canadian HEA community, but also with an eye toward capitalizing on technical expertise gained from fabrication, implementation, and calibration of the ASTRO-H metrology system. Involvement with [Athena] is consistent with CSA's mandate of growing experience and capability.*

The Athena is the second large class mission in ESA's Cosmic Vision. Its planned launch is in 2028, and it is budgeted at approximately 1.4 billion €.

The selection of Athena by the LRP reflects the growing number of Canadian astronomers working in high-energy astrophysics, and the recognized importance of multiwavelength astronomy.

The mission's science goals are reflective of the broad interests in the Canadian community. The primary questions it will confront are:

(1) Where are the hot baryons and how do they evolve?

(2) How do black holes grow and influence the Universe?

(3) What is the astrophysics of the hot and energetic Universe?

Athena will provide an order of magnitude more collecting area than the largest current X-ray telescopes using light-weight silicon pore optics. It will include two instruments: The X-ray Integral Field Unit (X-IFU) and the Wide Field Imager (WFI). The X-IFU is a calorimeter that will provide high spectral resolution between 0.2 to 10 keV over a 5-arcminute field-of-view. The sensitivity and field-of-view are order-of-magnitude improvements over what was available with the short-lived Hitomi mission. The WFI is a spectrometer and imager with a FOV of 40 square arcminutes. It will achieve charge-coupled device (CCD)-type spectral resolution over a large field – ideal for deep observations of the cosmic X-ray background.

The Athena mission has been our highest rated mission since the 2010 LRP. Recent events have opened the possibility of a Canadian contribution that must be investigated at an agency level. Potential areas of contribution are discussed in detail in Section 2.3.6, but include contributions to the spacecraft (e.g. metrology). The overall level of interest in the Canadian community for the Athena mission remains high.

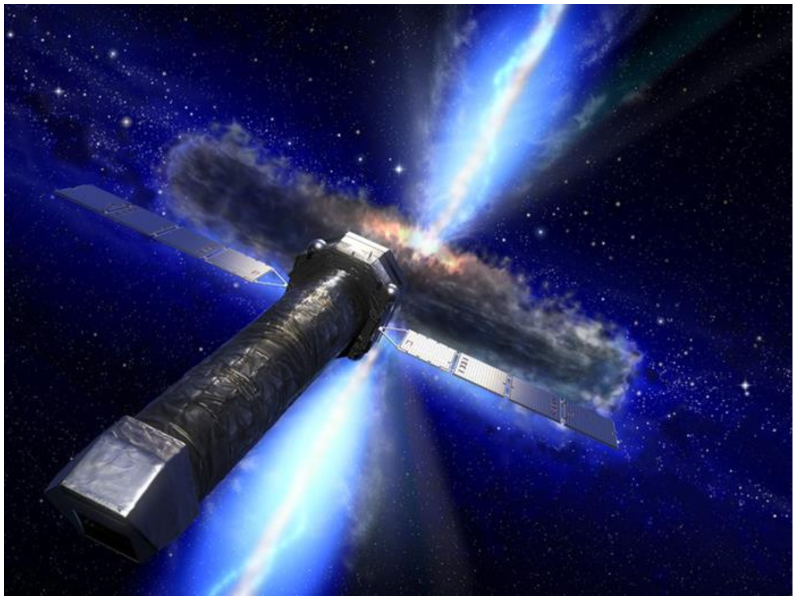


Figure 2-15 ESA's Athena X-ray Observatory, is planned to survey a violent Universe of exploding stars, black holes and million-degree gas clouds. But simply focusing X-rays is no easy task: they reflect only side on, like stones skimming along a pond. So ESA has pioneered the new technology of silicon pore optics – the careful robotic stacking of thousands of silicon wafers – to provide improved resolution and a greatly enlarged collecting area compared to current X-ray missions. ([6])

2.3.6.6 The Lynx Surveyor Mission

Lynx, formerly X-ray Surveyor, is a notional earth-orbiting X-ray observatory planned for the 2030s.

Led by NASA, the Mission Concept Study being prepared for submission to the 2020 US astronomy decadal review envisions X-ray imaging and spectral capabilities far superior to any existing or planned X-ray mission. The concept study is being conducted by the Lynx Science and Technology Definition Team commissioned by NASA in 2016. Composed of 31 scientists from North America, Europe, and Asia, the study is being led by Drs. Alexey Vikhlinin of Smithsonian Astrophysical Observatory (SAO), Feryal Ozel of the University (U.) of Arizona, and Jessica Gaskin of NASA/Marshall Space Flight Center (MSFC). Brian McNamara of the U. of Waterloo serves as an International Observer representing Canada. While the observatory's notional capabilities are under development, its instrument suite is expected to include a wide-field imager, a large-format, high-spectral resolution micro-calorimeter array, and a high-throughput grating spectrometer. The observatory's light-weight, sub-arcsecond optics will offer a collecting area and grasp that exceeds current capabilities by at least an order of magnitude. The transformative science realized by Lynx includes:

- detection and characterization of first accretion light from massive black holes in the early Universe,
- detecting and studying the missing baryons surrounding galaxies and in the cosmic web, measuring plasma motions near massive black holes,
- understanding how accretion energy is generated by black holes and its impact on large scale structure,
- understanding how cosmic feedback from SN explosions and massive black holes governs the growth of galaxies over cosmic time,
- understanding SN and the late stages of stellar evolution,
- understanding the origin of gravitational waves and other high energy phenomena.

2.3.6.7 Summary of X-ray Payloads

Table 2-5 Summary of X-ray Payloads

Mission	Agency	Launch	Status	Capability	Science Objective Addressed
Arcus	NASA (MIDEX)	2022	Phase A	Spectroscopy	HEA-01, HEA-02
Athena	ESA (Cosmic Vision L2)	2028	Phase A	Spectroscopy and Imaging	HEA-01 - HEA-04
Diffuse Intergalactic Oxygen Surveyor (DIOS)	JAXA (Small mission)	2028	Under Study	Spectroscopy	HEA-02
eXTP	IHEP of Chinese Academy of Science	2020-2025	Under Study	Spectroscopy, Timing, Polarimetry, All-Sky Monitor	HEA-01, HEA-04
Focusing On Relativistic universe and Cosmic Evolution (FORCE)	JAXA	2030	Under Study	Broadband spectroscopy and imaging	HEA-01 - HEA-04
High Energy X-ray Probe (HEX-P)	NASA (Probe)	2028	Under Study	Broadband spectroscopy and imaging	HEA-01 - HEA-04
IXPE	NASA (SMEX)	2020	Phase A	Polarimetry	HEA-01, HEA-04
Lynx X-ray Surveyor Mission	NASA (Large)	2030	Under Study	Imaging and spectroscopy	HEA-01, HEA-02, HEA-03
PolStar	NASA (SMEX)	2025	Under Study	Polarimetry	HEA-04
PRAXyS	NASA (SMEX)	2020	Phase A	Polarimetry	HEA-04
STAR-X	NASA		Under Study	High resolution, wide-field imaging and timing	HEA-01, HEA-02, HEA-03
XARM (Hitomi-2)	JAXA / NASA	2021	Development	Spectroscopy	HEA-01, HEA-02
Transient Astrophysics Observer on ISS (ISS-TAO)	NASA (MIDEX)	2022	Phase A	Imaging	HEA-01, HEA-04
XIPE	ESA (Cosmic Vision M4)	2026	Phase A	Polarimetry	HEA-01, HEA-04

2.3.7 *HEA – Canadian Instrument Development for Space*

Canada does not possess strong heritage in technology development for HEA. Even so, we create opportunities by providing IPs with key Canadian technologies that enhance their missions. In return, Canadian researchers are given leadership roles on missions and access to new data. Recent examples include successful delivery of the metrology system (i.e. Canadian Astro-H Metrology System (CAMS)) for the JAXA-led Astro-H mission (Hitomi), and the detectors and read-out electronics for UVIT on ISRO's Astrosat.

Capitalizing on these opportunities not only benefits researchers, but generates positive repercussions for Canadian industry. The development of the CAMS is an excellent example of such positive feedback at work. Neptec Design Group built on their expertise with space qualified optics and laser systems to create a high-resolution laser metrology system for Hitomi that can achieve micrometer resolution. Neptec has since obtained contracts from ESA to further develop the metrology system and several inquiries for similar alignment systems for other space missions. Moreover, these potential space missions are not exclusively X-ray missions, thus spawning new possibilities for Canadian astronomers.

The CAMS experience was fraught with significant programmatic challenges, but it was highly successful in the end, leaving JAXA keen to work with Canadian industry and researchers in the future.

2.3.7.1 Key Canadian Technologies and New Development

Some existing expertise that could be enhanced and adopted for X-ray missions:

- Laser metrology and sensor systems
- Optical subsystems, imagers, star-trackers
- Electronic subsystems for science instruments
- Multiplexers and switches
- Robotic systems
- Testing facilities
- Ground segment and data archiving

Broadband spectroscopy, large effective area, and wide FOV imaging require long focal lengths. This can be achieved with long rigid structures or optical benches that extend in orbit. In both cases, metrology systems are required. Athena, Arcus, POLStar, HEX-P, and FORCE would all require metrology systems. For most missions, an “off the shelf” system is not sufficient and some level of development is required. Furthermore, while a metrology system qualifies as a spacecraft component it directly improves the quality of science data and can be presented as a contribution to the science teams.

All astronomy missions require the usual spacecraft components (e.g. star trackers, sun sensors, baffles) and Canada has delivered quality components for past missions. We certainly have the expertise to extend this list to include, for example, communication, propulsion, and power systems. This would allow academics to team up with new industry partners, generating new capacity for industry partners and mission buy-in for the Canadian science team.

Likewise, all space missions require ground segments and data archiving. Canada provides ESA with advanced deep space antenna systems that could be leveraged for involvement on science missions. Canada is also world renowned for the systems and products produced by the Canadian Astronomy Data Centre (CADC). Supporting data archiving activities for future space missions is welcomed by many international agencies.

In seeking new opportunities, one can envision ways the CSA can work with new industry partners to develop hardware for X-ray missions. There are several Canadian companies that manufacture radiation detectors for medical imaging and security purposes. This is not unlike the technology used in HEA for our active shields or directly for detection of high-energy photons. While these companies do not appear to have expertise in developing space hardware there is the potential for partnering with established Canadian space industry. This would require substantial commitment by industry and the CSA.

Some spectroscopy missions like Hitomi and, in the near future, XARM use micro-calorimeters operating at milli-Kelvin temperatures to achieve high spectral resolution. Largely developed for ground-based, low-frequency astronomy, university labs and industry in Canada have directl relevant experience with low-temperature electronics that can be cultivated for space use. Further developing of multiplexing readout techniques for transition-edge sensors for X-ray space astronomy applications is highly desired.

A potentially promising partnership is between the CSA and the Canadian Light Source (CLS) as an X-ray test facility. During the Hitomi project, the CLS was used, without CSA participation, to calibrate some of the Soft X-ray Spectrometer (SXS) optical blocking filters. A similar project is being considered now as a potential contribution to the Hitomi recovery mission, XARM. The CLS offers several beamlines that can be useful for any X-ray mission.

2.3.7.2 Direct Contribution to the Athena Mission

Potential means to participate on the Athena Mission have recently materialized. The mission is currently in Phase A and a Mission Consolidation Review (MCR) has been completed. While the mission has been confirmed technically feasible, one result of the MCR is that the ESA cost for the telescope and spacecraft is about 20 per cent over budget. ESA is now actively soliciting IPs that can contribute to the telescope and spacecraft. All spacecraft components can serve as contributions to the mission.

The most tangible contribution is a metrology system. Athena will not possess an extendible optical bench, but the long focal length, moving components, and desire for high angular resolution and wide-field imaging demand a metrology system. We are poised to build on our success with Hitomi and work with ESA to produce the alignment system.

However, all aspects of the spacecraft system should be considered. Many components may generate interest for Canadian industry partners. A general list of components that are required by ESA are tabulated in Table 2-6. A detailed list will be provided to the CSA.

Table 2-6 General components required by ESA

Type	Description
Attitude and Orbit Guidance Navigation and Control (AOGNC)	Sensors (Star trackers, gyros, sun sensors, metrology); thrusters; axis stabilizer
Thermal	Mirror heaters; MLI; Instrument radiators;
Mechanisms	Moveable mirror using a hexapod; mirror cover; venting mechanism; sun shield
Communications	High gain antenna; low gain antennas; x-band system
Data handling	On board storage for science and housekeeping data
Structure	Carbon Fiber Reinforced Polymer (CFRP) structure; Telescope with stray light baffles; focal plane array packaging; vibration isolation
Propulsion	Propellant (Hydrazine); tanks
Power	Fixed deployable solar array

2.3.7.3 HEA – Conclusions

Canadian members of the HEA community are among the top international researchers in their respective fields. However, the community has not historically included academics or industry partners that work on X-ray instrumentation. The HEA community will not lead an X-ray mission in the near future. Consequently, our relationship with the CSA is different than other fields of astronomy. We look to partner with international agencies by contributing essential software or hardware mission components that are not necessarily related to the X-ray detectors. In return, Canadian researchers are involved in science team activities and access to data.

We successfully built and delivered the metrology system for the Japan-led Hitomi mission, and the UV detectors and electronics for the ISRO-led Astrosat mission. These are examples of key technologies that were provided to international agencies for access to science data. The HEA community looks to profit from all space expertise available in Canada. Accordingly, we require a level of flexibility from the CSA so we can take advantage of opportunities as they arise. In addition, the CSA should investigate means to support Canadian astronomers that are involved in international mission collaborations without direct CSA involvement.

Such investments can pay dividend in the future by providing Canadian researchers with mission experience and enhancing CSA visibility internationally. All this said, we do suggest that the CSA explore potential relationships with Canadian companies that hold expertise in hardware development for the medical and security industries, as well as in ground-based radio astronomy. These are possible foundations for developing X-ray detectors and components for space use in the future.

HEA encompasses all areas of astronomical research from planets to cosmology. The detection of high-energy photons is difficult and detector technology is distinct from other wavelengths. Our approach toward missions may also appear distinct since bigger is not necessarily better in HEA. The missions that researchers use are necessarily diverse as one mission cannot serve all purposes. The community expresses interest in missions of various sizes, including small team-based explorer type missions to the large “great observatory” type missions. The Athena mission, with a 2028 launch date, remains the top priority for the Canadian community. Recent events in Europe indicate a possibility for IPs to contribute by supplying spacecraft components. The level of buy-in this would generate for Canadian scientists needs to be explored.

2.3.8 References

[1] *Based on models from Robinson et al.*

[2] *Adapted from Seager et al. 2015*

[3] *Source: NASA/JPL-Caltech*

[4] *Source: SDSS, CXC/IoA/ACFabian, NRAO/VLA/GBTaylor and MLGendron-M./JHlavacek-L.*

[5] *Source: NASA/CSC/SAO*

[6] *Source: ESA*

3 Planetary Exploration in Canada Overview

Planetary exploration involves investigating the characteristics of planets and planetary bodies (e.g. moons, asteroids and comets) in our Solar System, including the geological record preserved from their surfaces, samples, and interiors; the composition and evolution of their atmospheres; the interaction of their surfaces, magnetic fields and atmospheres with the solar wind. From these characteristics we can infer which environments in the Solar System may have been, or are presently suitable for life.

The goal of **astrobiology** (AB; Section 3.1) is to answer the fundamental question *Does life exist elsewhere, other than Earth?* Answering this question requires the detection and differentiation of signs of life (biosignatures) from characteristics produced without the involvement of life (abiosignatures). Research in this area requires the study of life in the lab and the field, in particular where it is near its limit on Earth, in order to characterize biosignatures to better enable their detection. Canada is well-endowed with a diversity of natural environments that meet this criterion, including those found in Arctic hotsprings and in the deep subsurface; these environments serve as analogues for similar environments anticipated or known from other planetary bodies in our Solar System. Instrumentation developed for the detection of biosignatures, such as Raman microspectroscopy and micro (“lab-on-a-chip”) life detection platforms, can be tested in these Canadian analogue environments, providing important field knowledge for technology development. Flight versions of these instruments would play a key role in planetary exploration, and could be involved in everything from providing contextual information for the selection of samples returned from Mars, to the *in situ* analysis of the surface of the icy moons such as Europa, to aiding astronauts in the exploration of planetary surfaces. A key aspect of astrobiological planetary exploration is **access** to the environments of interest: micropenetrators, drills and microrovers are all platforms that could provide such access; the additional ability to sterilize equipment and instrumentation would make ‘special regions’ (environments with a higher probability of life being present today) more accessible.

The composition and chemistry of gaseous components, aerosols, and dust in **planetary atmospheres** (PAT; Section 3.2) provide a record of the evolution of the atmosphere over time, its interaction with the planetary surface, and with the planetary space environment. Canada has proven expertise in this area, from laboratory simulation and computing facilities, to the Meteorological Package on the 2008 Phoenix Mission to Mars. In this context, Canada is well-positioned to develop the next generation landed Light Detection and Ranging (LiDAR) instrument – a Raman LiDAR – which would advance the study of the Martian atmosphere, including identification of atmospheric aerosols, ice water content in clouds and precipitation, and processes involved in the deposition of water ice on the surface. Canada’s world-leading position in FTS technology for observing atmospheric composition, and experience with flown instruments on Earth and Mars, provides a significant and advantageous position from which to consider application to other planetary atmospheres. Provided that preparatory research needs (specifically, atmospheric modeling and laboratory experimentation) are met, the high technological readiness level of many Canadian atmospheric instruments places targets as diverse as Venus, Titan, the Gas Giants, and Pluto within reach.

The exploration of planetary surfaces from a geological perspective is currently undergoing a shift in perspective and emphasis: just as Canada was mapped over 150 years ago in order to find resources to build a country, planetary bodies in our Solar System are being prospected, either for future resource exploitation for use on Earth or in space (such as platinum group metals), or for *in situ* resource utilization in human exploration (such as water on asteroids or Mars). Canada is a world leader in mining and mineral exploration; the synergy between terrestrial activities and near-future extraterrestrial resource exploration leads to a significant potential for Canada to be actively involved in these types of activities.

While **planetary geology, geophysics, and prospecting** (PGGP; Section 3.3) encompasses a range of investigations – mostly relating to the geological record of solid planetary bodies in the Solar System – instrumentation including radar, LiDAR, in situ X-ray Diffraction (XRD), Raman, and gravimetry can be applied to many solid body targets. Analogue research, sample curation and analysis, and data analysis, are considered essential types of preparatory research for Canada's involvement in this area of planetary exploration. The study of the flux of meteorites to Earth and of their asteroid parent bodies as potential impact threats provides knowledge that contributes to the potential survival of human civilization.

The harsh, radiation-rich environments present in near-planetary space is the result of interaction between the Sun and the planets and other bodies in the Solar System; an understanding of **planetary space environments** (PSE; Section 3.4) is a necessary prerequisite to enable planetary exploration. Detailed study of the physics of these environments provides the ability to forecast and mitigate potentially negative effects on robotic and human explorers. Canada has a rich history of research in this area; the first Canadian satellite, Alouette-1, carried instruments to measure energetic particles in the ionosphere. The 2017 ExAlta-1 CubeSat follows in that tradition, and is a part of the ESA QB50 program to provide in-situ measurements of the lower thermosphere. Accordingly, flight instrumentation is relatively mature, and includes magnetometers, radio receivers, low- and high-energy particle detectors, as well as imagers in the UV, visible and near-IR parts of the spectrum. While many of these instruments have near-Earth space heritage, they can be readily applied to investigations of similar environments around the Moon, Mars and the radiation-rich Gas Giants and their satellites.

There exist many areas of common interest, and commonalities in investigations among the four topics that comprise Planetary Exploration. Characterization and detection of biosignatures in the context of planetary exploration (priorities AB-01 and AB-02) requires contributions from planetary geologists, geophysicists and geochemists to provide insights into the physical, spatial and temporal boundaries of habitable planetary environments (priority PGGP-01). Understanding the origin and distribution of water and other volatiles in the solar system (priority PGGP-03) is an important component of this, and contributes to planetary atmospheres as well, as it relates to the transport and cycling of volatiles between the atmosphere, surface, and subsurface of planets such as Mars (priority PAT-01). Investigations of the solar wind and its interaction with the upper atmosphere of Mars (priority PSE-02) are necessary to fully understand the evolution of the Martian atmosphere (priority PAT-02). Understanding Mars atmospheric chemistry, including quantifying trace gases (priority PAT-02) contributes to the determining whether trace gases can be considered biosignatures (priority AB-01). Magnetometry of the Moon and Mars (priorities PSE-02 and PSE-01-02, respectively) contribute to elucidation of the geologic histories of these planetary bodies and their planetary interior structures (priority PGGP-04); and the characterization of the radiation environment around the Gas Giants (priority PSE-01) is crucial to understanding the evolution of the icy satellites and their potential for life (priority AB-02).

All investigations outlined in this section, involving the exploration of planetary surfaces, atmospheres and space environments, contribute to paving the way to human exploration (Space Health) and to our future as a species, from the identification of resources (priority PGGP-02); to knowledge of the threat of impacts on Earth (priority PGGP-05); to the forecasting of space weather around Earth, the Moon and Mars (priorities PSE-01-04 and PSE-02-02); as well as to the understanding of exoplanetary formation and evolution and to the potential for life elsewhere in our Universe (Space Astronomy).

Underlying all the investigations in this section is the need for community-building to foster communication within and between disciplines, and to enable the prioritization of research. Support of students and especially postdoctoral researchers is essential for training the next generation of Canadian space researchers. Involvement of Canadian researchers as Co-Investigators and Participating Scientists on international planetary exploration missions is considered of high value both for Canadian science and profile, and an excellent return on investment for the CSA. The need for support of ground-based programs, facilities and infrastructure – including analogue research, sample and space data analysis, and modeling – has never been greater, given that these comprise the preparatory research that undergirds the exploration of our Solar System.

3.1 Astrobiology

Community Report from the Planetary Exploration Topical Team on Astrobiology

Table 3-1 Planetary Exploration - Astrobiology Topical Team

Name	Affiliation
Greg **Slater** (Chair)	McMaster University
Ed Cloutis	University of Winnipeg
Penny Morrill	Memorial University of Newfoundland
Claire Samson	University of Ottawa
Lyle Whyte	McGill University
Richard Leveillé	McGill University
Nick Cowan	McGill University
Rene Doyen	Université de Montreal
Neil Banerjee	University of Western Ontario
Barbara Sherwood Lollar	University of Toronto
Mike Daly	York University
Greg Slater	McMaster University
Gordon Osinski	University of Western Ontario
Ralph Pudritz	McMaster University
Chris Herd	University of Alberta
Alan Scott	Honeywell
Jackie Goordial	McGill University
Haley Sapers	McGill University/Caltech
Allyson Brady	McMaster University
Ben Pearce	McMaster University
Sian Ford	McMaster University

3.1.1 Introduction to Astrobiology in Canada

Astrobiology is a field of tremendous interest to scientists, engineers and the public as it seeks to answer one of the most basic human questions: "*Are we alone in the universe - Does life exist beyond the Earth?*" Indeed, the search for life on other solar system bodies is and will be a driver of planetary exploration research and missions in the coming decades especially in terms of discovering past or present life on Mars, the outer icy moons, and in exoplanet research. Fundamentally, answering this question requires the ability to detect and differentiate signatures of life, or biosignatures, from those that arise from abiotic processes, or abiosignatures. To achieve this, astrobiology must therefore: i) develop an understanding of what constitutes a biosignature, how it is formed and preserved, and how it may be differentiated from signatures of abiotic processes, and ii) develop the methods by which biosignatures may be detected. Astrobiology is necessarily a multidisciplinary research field that brings together astronomers and astrophysicists, planetary and Earth scientists such as geologists, geophysicists and geochemists, as well as microbiologists, biologists, biochemists and chemists. Such multidisciplinary research is recognized as a key component of current and future scientific endeavor, resulting in innovation within the fields involved and contributing to the development of science and engineering, and resulting innovation and economic growth in Canada. With a wealth of expertise and relevant analogue environments, Canada can and should play an active role in astrobiology research and astrobiology space missions.

There is a strong and highly productive astrobiology research community in Canada that is well positioned to contribute to future discoveries and innovations. This includes, but is not limited to: fundamental research and instrument development and testing aimed at characterizing biosignatures and abiosignatures on Earth in laboratories and analogue sites in Canada and internationally, current and planned space missions, and exoplanet detection and characterization.

Canadian participation in future astrobiology related space missions is a crucial component to placing Canada at the forefront of research expertise in all the disciplines involved. This is particularly important because access to future samples returned to Earth for analysis is often dependent on mission contributions. Such participation requires Canada, and Canadian researchers, to be prepared to address the scientific questions that will drive future missions. It also requires that Canada and Canadian researchers be adaptable such that their expertise, instrumentation and science priorities can relate to and enhance future missions that are not always well defined at the earliest stages. That is, the science priorities of the Canadian research community need to be sufficiently broad that they can contribute to whatever missions are selected in the coming years.

The overarching scientific focus of astrobiology is the detection of biosignatures. The ability to determine what represents an unambiguous signature of life, extinct or extant, that cannot be produced by abiotic processes (i.e. abiosignatures) and to detect such signatures is the keystone to astrobiological research. The scientific objectives and investigations in this report focus on developing Canadian capability and capacity to contribute to addressing this question via participation in space missions beyond the mid-2020s. The majority of these objectives and investigations are focused on applications relevant to Mars or the Icy Moons (Enceladus, Europa, Titan, Ganymede) as these are the most accessible to space missions. Distinct considerations relevant to biosignature detection as it pertains to exoplanet searches are also considered. However, it must be recognized that all of these objectives rely on our understanding of the processes and signatures of life on Earth, including in particular our understanding of its origins and early history.

As such, the Astrobiology TT has identified a total of five objectives for future Canadian Space Exploration. This list has been prioritized as follows:

- AB-01 Biosignature Characterisation (87.5)
- AB-02 Biosignature Detection (97.0)
- AB-03 Accessing the Subsurface for Astrobiology (90.0)
- AB-04 Accessing Special Regions (93.0)
- AB-05 Exoplanets: Characterization and Detection of Biosignatures (76.0)

3.1.2 AB-01: Biosignature Characterisation: Characterization of unambiguous biosignatures and development of detection methods applicable to space missions

(Prioritization score: 87.5)

(1) Science Question

The foundational question that must be answered to successfully search for evidence of life beyond the Earth is: "*What represents a signature of life?*" This question has become all the more central as space missions focused explicitly on the search for life represent the next generation of space exploration (e.g. Mars 2020, ExoMars). Given the significance of this research question, it can be expected that further missions will extend and expand this focus on the detection of evidence of life (extinct and/or extant). However, the scientific community also increasingly recognizes that unambiguous biosignatures for all but the most obvious cases (e.g. technology, macrofossils, macro-organisms) are difficult to define and detect. And while we might hope for a single "eureka" moment of life detection, it may more realistically be an accumulation of many lines of evidence that finally answer this question. This perspective makes developing our understanding of what constitutes a biosignature all the more crucial. There are a number of opportunities for Canada to make leading contributions to this task. The investigations outlined below describe some of the key opportunities that are present at this time. As research develops it is expected that new insights and understanding will generate further opportunities. As such these investigations represent a starting point on which to build toward the answer to the question of "*are we alone?*". While primarily preparatory activities, these investigations are critical to the development of mission concepts and strategies, instrument requirements, and the eventual instruments themselves that will help make important discoveries in future missions.

(2) Science Approach

Addressing these research objectives requires investigations on several fronts. First, we must define biosignatures and develop our understanding concerning how they are distinct from signatures produced by abiotic processes (abiosignatures). This is required for each biosignature that is proposed be they an organic molecule or set of organic molecules, isotopic signatures, or mineralogical or morphologic signatures. And the only way that this understanding can be developed is to investigate the one example of life we have, life on Earth. As such preparatory analogue research activities investigating the origins, early history and signatures of life on Earth, in which Canada is well suited to play a significant role, continue to represent the key to astrobiological research and are the first investigation proposed.

(3) Past Canadian Heritage

Canada has established and recognized expertise in many research and engineering areas relevant to biosignature detection. This begins with Canada's notable expertise and access to a wide range of analogue environments that enable the preparatory activities for biosignatures characterization and detection to be achieved. These environments include: some of the most ancient rocks in the world; access to deep subsurface systems via partnerships with the mining industry such as those that have identified the oldest waters on Earth, cold and desert polar regions as environmental analogues to Mars and/or the icy moons; hydrothermal and serpentinizing systems where chemical disequilibria provides the energy for life; numerous extreme natural systems where microbial communities exists under unusual conditions enabling the limits and mechanisms of life, and the associated biosignatures, to be tested; and a range of meteorites, including the unique Tagish Lake specimen. Overall, Canada has established and recognized expertise in a broad range of research areas spread across the country.

(4) Rationale for Canadian Priority

The requirement of characterizing and detecting biosignatures makes Earth based analogue research crucial to the field of astrobiology. The established astrobiology community in Canada that represents researchers from across the country have been, and are currently making, significant contributions to this research area. However, given the close relationship between astrobiological analogue research and many fields of Canadian expertise (e.g. Earth Science, geobiology, microbiology, geochemistry, geophysics, etc.) there is a large opportunity to build and broaden Canadian expertise in biosignatures research by expanding the community of researchers involved. Further, the close ties between Canadian researchers and the space science industry (e.g. through science instruments on missions and prototype development) has led to numerous research grants and projects; this foundational relationship holds great promise for development of further expertise and technology.

(5) Possible Mission Opportunities

Positioning Canadian expertise as a leader in the definition, detection and the assessment of preservation of biosignatures in the international space science community will make Canadian scientists invaluable to mission development and execution. This involvement will integrate Canadian researchers among the international leaders who are overseeing site selection, defining mission objectives, and determining instrument requirements and other mission parameters. Further, Canadian researchers will be integral to interpretation of data obtained via either in situ or sample return missions.

3.1.2.1 AB-01-01: Preparatory Research: Characterization of biosignatures and their preservation in Modern and Ancient Earth analogue systems

(Prioritization score: 81.4)

The wide range of environments for life on Earth, both represented in the modern environment and preserved within the geologic record of the origins and history of life, represent the only template we have to define what represents a biosignature. It is the only template from which to develop our understanding of how life and its associated signatures might vary under the different conditions present on other planets/moons. Ongoing work to identify organic, mineralogic, isotopic and morphologic signatures of biological activity provides the foundation for astrobiology, critical for any future life-detection endeavours. Analogue based research work must be continued and must include both characterization of modern systems where extant life is active, as well as translation of this understanding to ancient systems preserved in the rock record. Given that life on Earth represents the only example and defining template we have for evidence of life, preparatory activities to elucidate biosignatures and their preservation in a wide range of environments on Earth must be prioritized. Identification of unambiguous biosignatures will be the cornerstone of astrobiology in all contexts. Environments that should be investigated within preparatory activities include: Subsurface environments (as biosignature preservation on other planets /moons is expected to be highest there), hydrothermal environments, hot springs, serpentinizing environments, locations of high water rock reaction, sedimentary environments (marine/lacustrine) and saline and cryo environments (particularly associated with the subsurface), and environments and investigations that provide insight into the mechanisms and signatures of the origins of life.

In all of these environments there is a need to characterize microbial communities, their metabolic capabilities, and the biosignatures associated with either their metabolic activities or the microbes themselves using the most state of the art approaches. This research provides a comparative point against which new instrumentation developed (Objective AB-02) can be compared. A component of this research must be identification of locations where preservation of biosignatures of past life is the most likely and determination of the mechanisms which control this preservation. Such understanding will enable site selection on Mars or Icy Moon environments and enable the characterization of the biosignatures that may be expected to occur in at these sites. Ultimately, understanding the mechanisms of biosignature preservation on Earth and the geologic environments where these processes are optimized will enable selection of either in situ or sample return targets on Mars for biosignature analysis.

3.1.2.2 AB-01-02: Preparatory Research: Characterization of signatures of abiotic systems on Earth

(Prioritization score: 78.0)

While the field of biosignatures has a long legacy, it is recently engaging in a dynamic evolution driven in part by new mission discoveries (e.g. Curiosity, Kepler) but also by the recognition that the examination of abiosignatures has been an under-investigated corollary of biosignature research. For example: "The scientific significance of any potential sign of past life (sic. biosignature) comes not only from the probability of life having produced it, but also from the improbability of non-biological processes producing it" (Mars 2020 Science Definition Team Report). Thus, working to identify signatures of abiotic systems/processes (abiosignatures) that must be differentiated from biosignatures is an essential compliment to biosignature characterization. On earth, abiotic signatures can be found in many systems, including those where biology might be expected to exist. Progress has been made in some systems such that biogenic versus abiogenic minerals can be recognized, and recent research has shown that biogenic minerals may be distinguishable from their abiogenic counterparts based on compositional, isotopic, and morphological differences.

In addition, the presence of organic molecules and patterns in their chemical distributions and properties (e.g. chirality) and associated isotopic ratios can provide some of the most often used biosignatures on Earth. However, it must be demonstrated that these differences are robust, even under the different conditions that may be expected to occur on other planets/moons. Investigations focused at the transition from abiotic to biotic systems, that is at the origins of life, provide a key potential means to address this distinction. In addition, characterization of abiosignatures and their mechanisms of formation and preservation should be carried out in a similar suite of environments as is investigated for biosignatures including: Subsurface environments (as biosignature preservation on other planets /moons is expected to be highest there), hydrothermal environments, hot springs, serpentinizing environments, locations of high water rock reaction, sedimentary environments (marine/lacustrine) and saline and cryo environments (particularly associated with the subsurface).

3.1.2.3 AB-01-03-Sample Analysis Investigation: Characterization of abiosignatures from small bodies (meteorites, asteroids)

(Prioritization score: 76.0)

Small bodies are comets and asteroids (minor planets). Along with meteorites, these objects provide our best probe into the conditions present when the solar system was formed because many of them have been unprocessed or minimally processed since they formed. Based on our understanding of formation, small bodies inherently represent abiotic systems. Characterization of small bodies and meteorites thus represent a key insight into abiotic signatures that biosignatures must be distinguished from. In addition, the distributions of organics on meteorites give one of the best windows into the organics that may have been present as the building blocks for the origins of life. Currently, meteorite samples are accessible, including highly pristine samples of Tagish Lake, a unique Canadian resource. Analysis of these materials provides the foundation of this characterization.

However, ultimately, sample return of pristine astromaterials provides an essential ground-truth of the current organic and water content. All asteroid classes are of interest but the priority should be given to comets and carbonaceous asteroids. Characterization should include organic carbon content and in particular distributions of organic molecules and their chirality and isotopic compositions. Distributions of organic molecules and variations associated with variations in material properties and processing. These activities will inherently require the development of appropriate sample handling and storage facilities that can preserve sample integrity and analytical detection limits. This will provide insight into processing of molecules delivered to the early Earth, what may have happened on the early Earth, and space weathering that is ongoing.

3.1.3 AB-02: Biosignature Detection: Development of instrumentation and criteria for the detection of biosignatures on planets/moons/small bodies

(Prioritization score: 97.0)

It is obvious that the ability to detect (i.e., measure) biosignatures on astrobiological targets (planets/moons/small bodies) is fundamental to their assessment and interpretation. The instrumentation developed for Mars 2020 and ExoMars represents a step toward increased capabilities to detect biosignatures. However, in situ analytical capabilities remain far more limited than those available in laboratories on Earth. Further, the technologies currently being utilized cannot be deployed in all contexts or for all purposes. Thus there remains a need to develop further technology to detect and interpret biosignatures and a concurrent opportunity for Canadian contributions to this work.

(1) Science Approach

The next tier of opportunities for Canadian space scientists to contribute is via development and expertise in the detection of biosignatures using space flight capable instrumentation. Canadian contribution may most effectively be realized via identification of specific approaches that are somewhat distinct from the thrusts of major research groups globally, thus enabling a unique contribution to be made. The investigations outlined below describe the proposed approach to achieve these goals.

(2) Rationale for Canadian Priority

The Canadian expertise in the identification of biosignatures and abiosignatures positions Canada well to develop instrumentation capable of detection of these biosignatures under relevant conditions. Canada has established heritage in instrument development (OSIRIS-REx Laser Altimeter (OLA), Alpha Particle X-Ray Spectrometer (APXS), Phoenix Meteorological Station (MET) and LiDAR) and has specific potential with laser-based imaging and spectroscopic instruments (Raman- laser-induced breakdown spectroscopy (LIBS) - laser-induced fluorescence (LIF)) and a next generation Micro life Detection Platform based on Nanopore sequencing currently under development and being supported by the CSA. Canadian scientists are already involved in the SuperCam instrument (NASA Mars 2020 mission), which features both Raman and LIBS spectroscopy capabilities.

(3) Possible Mission Opportunities

Development of instrumentation capable of specific applications and/or specific deployment capabilities (size/sterilization/robustness) would allow Canadian instrumentation to be deployed in a range of secondary payload/small mission scenarios or as a contribution to a larger mission led by one of our partners. The instruments and techniques mentioned above and below could potentially apply to several landed missions on different planetary bodies. As such, they are considered versatile and there will likely be multiple opportunities for flight in the future.

3.1.3.1 AB-02-01 Instrument Investigation: Development of instruments/methods for biosignature detection

(Prioritization score: 88.6)

Detection of biosignatures (mineral, organic, or isotopic) within ancient rock, such as those accessible on the Martian surface, faces many challenges. Biosignatures must be preserved over relevant timeframes under prevailing conditions. Given the harsh comic ray flux and geochemical conditions on the Martian surface, the subsurface is considered the optimal place to detect biosignatures. The search for biosignatures in extreme environments and ancient rocks on Earth requires development of methods and instrumentation capable of detecting the biosignatures defined in Objective AB-01. It also necessitates the ability to distinguish results from those produced from abiotic processes. Such understanding is crucial as the number of samples that will be able to be analyzed is small. In addition, the study of subsurface and ancient rock terrains on Earth will enable development and testing of instrumentation capable of biosignatures detection on Mars. This may include gas chromatography (GC)/mass spectrometry (MS), Isotope-ratio mass spectrometry (IRMS), Raman or other spectroscopic means. The specific detection limits, comparison to blanks, scope of performance of these techniques needs to be defined based on balance between capabilities of Earth based laboratories and limitations associated with space flight payload and energy restrictions. Initial studies should include assessment of available methods and their realistic capabilities.

3.1.3.2 AB-02-02 Instrument Investigation: Instruments for detection of biosignatures on Mars

(Prioritization score: 90.5)

Development of instrumentation suitable for space flight deployment and in situ operation based on new technologies developed in AB-02-01 is an important next step to follow up investigation AB-02-01. Specific capabilities of instrumentation must be optimized and balanced with restrictions of energy and payload relevant to space flight.

GC/MS, Raman and other spectroscopic approaches are being developed that can achieve the required precision via rover or platform mounted deployment. The cost for such in situ analysis is far less than that for returned samples or astronaut lead sampling and analyses. While the precision may be lower, this approach should be pursued as it provides a mechanism by which to maximize scientific productivity while balancing cost. In particular, such in situ analysis can be used as an initial search method to identify high priority samples for future sample return or astronaut led analyses.

Raman spectroscopy has emerged as a key technology in biosignature detection that is at a high enough Technology Readiness Level (TRL) that they have been scheduled on the upcoming Mars 2020 and ExoMars missions. Extensive applications of Raman spectroscopy to Earth based biosignature detection have demonstrated the potential of this technique. However, there are a number of variations in this technology that need to be explored to improve biosignatures detection and interpretation. These include: i) time gating (to mitigate the effects of induced fluorescence and to discriminate biogenic from abiogenic fluorescence, and allow Raman acquisition in daylight or for remote targets); ii) use of different excitation wavelengths to suppress or minimize induced fluorescence and enhance detectability of organic molecules; stand-off operation (tens of meters) enabling remote mapping of geologic environments and concurrent biosignature detection; system miniaturization; integration into multi-measurement systems (e.g. LIBS/Raman, Raman/fluorescence, Raman/ LiDAR). Canada has strong expertise and heritage in Raman spectroscopy with a number of Canadian space technology firms (e.g. Honeywell, MPB, MacDonald Dettwiler and Associates (MDA), National Optics Institute (INO)) and universities (e.g. York) pursuing the development of next-generation Raman spectrometers for geochemistry and atmospheric science, in both academia and government.

Significant progress in developing a new generation of smaller instruments based on nanotechnology and microfluidics is also an active area of research given their very low mass and energy requirements. For example, ultra-small DNA/RNA/Protein detection and sequencing devices built by Oxford Nanopore are currently being developed and tested by numerous groups in Canada and internationally for their potential for future robotic and manned missions to Mars, Europa and Enceladus. However, sample preparation and introduction mechanisms remain a key challenge to be addressed as well as determination of biomolecule detection limits and robustness of these technologies with analogue samples. Finally, once proof-of-concept is shown, integration and robotization of sample acquisition, biomolecule extraction, sample preparation and sequencing devices into an instrument platform needs to be achieved to increase TRL for future missions.

3.1.3.3 AB-02-03: Instrument Investigation: Flux measurements/biological experimentation

(Prioritization score: 73.5)

We have had limited ability to perform in situ manipulation experiments as part of missions to other planets/moons. Our current focus on analytical and sampling methods has resulted in missions dedicated to explorative space research, but we have limited hypothesis-driven controlled experiments. Ex-situ chambers, similar to those housed on Viking, would provide a space for manipulative experiments with live and killed controls, while in-situ chambers could monitor fluid (gas or liquid) flux on the surface, or in the sub-surface. A surface chamber could be similar to the flux chambers currently deployed in greenhouse gas studies (some developed by Eocene, a Canadian company), while a sub-surface chamber could resemble the packers/collars used today in studying fluids in the subsurface mines. The subsurface chamber would be developed in combination with the subsurface drill/scoop. All of the chambers would have sample transfer lines to analytical equipment and/or the ability to cache samples. Sample concentration methods may be required for analytical instrumentation (e.g. optimization of signal in low concentration environments).

3.1.3.4 AB-02-04 Sample Analysis Investigation: Detection of Biosignatures in Returned Samples

(Prioritization score: 92.5)

Detection of biosignatures in returned samples will require the development of lab instrumentation and analytical techniques that are at the leading edge of sensitivity, precision, and contamination control. There are a number of laboratories in Canada that have, or are capable of developing, the required technology and expertise. A key component of completing this type of analysis will be the assessment of analytical blanks associated with terrestrial samples. Associated with handling of such samples will be the requirement of establishment of sample handling and preservation facilities with strict protocols in place to avoid contamination. Participation in sample return mission development and instrumentation would be key to getting access to samples. Some of this work would address current missions (e.g. OSIRIS-REx). In addition, due to the similar need for minimization of contamination and proper handling techniques, support for studies of meteorites would not only help to develop the science necessary (see Investigation AB-01-03), but also help to develop sample handling and analyses strategies, and possibly new and improved techniques.

This investigation will also involve analogue field deployments to investigate sampling strategies and ultimately improve the science return from both the in situ analyses and the analysis of returned samples.

3.1.4 AB-03: Accessing the Subsurface for Astrobiology

(Prioritization score: 90.0)

It is generally considered that the most promising locations to search for evidence of extraterrestrial life in the solar system is in the subsurface of planets or moons where potential biosignatures are protected from hostile exposure at the surface. Fundamentally, the issue of access to astrobiological samples is as important as scientific instrument selection. In the case of Mars, the subsurface affords protection from solar UV radiation, super-oxides and perchlorates that may inhibit the ability to detect and interpret biosignatures (e.g. organics). It is reckoned that a depth of 1-3 m will be required in order to escape the negative effects of surface exposure and processing. For the case of Titan, penetrators may be designed to splash-down into Titan liquid bodies. Similar access to subsurface water may be an option for Enceladus' tiger stripes. In the case of Europa and Enceladus, access to the subsurface water is a more complex issue involving a solid ice layer that protects the subsurface from the vacuum of space. There is evidence in both cases of recent plumes of water ejected from the near surface but the depth of ice necessary for access to the liquid water reservoir is unclear. Nevertheless, in both cases, the water plumes suggest there may be breaches in the ice which may offer access points. In the case of Mars, Raman Laser Spectrometer (RLS) may represent a similar point of discharge of subsurface fluids to the surface, and remnant hydrothermal springs and/or impact structures may also offer opportunities to investigate material transported from the subsurface. Similarly access to subsurface environments may be available via geomorphologic structures such as lava tubes, sky lights, and eroded or excavated cliff faces.

3.1.4.1 AB-03-01: Space Systems Development: Penetrators / micropenetrators

(Prioritization score: 79.5)

There are several proposed methods for accessing subsurfaces that when combined with micro-instrument development offer important opportunities for biosignature investigations. Penetrators are applicable to all targets in that they offer the prospect of subsurface access with minimum mass delivery. Assuming a restriction of 300 m/s impact velocity (to minimize physical alteration to the surface/subsurface soil/ice), depth of penetration will be up to 3-5 m depending on the substrate. Penetrators offer direct access to the subsurface for simple scientific instruments. Sampling coring may be via microdrills. Onboard instruments may include accelerometers, temperature and pressure sensors as a basic payload manifest. Fibre optic sensors and other micro-sensors such as micro-cameras, electronic noses, nanopore and others are feasible for incorporation. There are many opportunities for robust micro-instrument development.

3.1.4.2 AB-03-02: Space Systems Development: Subsurface access from landed assets

(Prioritization score: 79.5)

From landed assets, controlled subsurface access is afforded through end effectors, drills and moles. End-effectors mounted onto robotic manipulators provide surface and shallow sampling of regolith (scoops) or specific rocks (robotic fingers) for analysis. To access greater depths, drills and moles are required. Drills provide coring capability to return subsurface samples to the landed asset for further analysis. The advantage of drills is its sampling capability but they necessarily introduce deployment complexities. Moles on the other hand are self-contained devices that provide subsurface penetration with greater deployment flexibility at a cost of greater engineering complexity. In both cases, the use of fibre optics allows the integration of sensor heads into the subsurface device to directly measure in-hole properties. The scientific instrument resides on the landed asset. This provides both contextual analysis for the sample and sample selection capability. Any fibre-optic based instrument in which a sensor head can be separated physically from the main instrument is suitable – Raman spectrometer, IR spectrometer, LIBS, confocal microscope or any hybrid thereof.

3.1.4.3 AB-03-03: Space Systems Development: Subsurface access by micro-rover

(Prioritization score: 80.5)

The CSA has developed prototypes of two separate micro-rovers with a tethered capability and varying instrument configuration (e.g. X-ray Fluorescence (XRF), imaging). These micro-rovers could potentially access two high-priority subsurface environments for sampling on in situ analyses: subsurface caves and subsurface aquifers. Subsurface caves (lava tube caves, ice caves/voids) could be accessed by using a micro-rover tethered to a larger rover or to some other anchor point. For example, a micro-rover could be dropped down a “skylight” in a lava tube cave. Similarly, a micro-rover could be sent down a steep slope to investigate surface deposits created by the emergence of subsurface water such as Mars Recurring Slope Linea (RSLs). (e.g. see Objective AB-04).

This investigation will seek to use a micro-rover in analogue field deployments as a proof-of-concept scenario for future missions.

3.1.5 AB-04: Accessing Special Regions

(Prioritization score: 93.0)

“Special Regions” are those areas considered to have the highest potential to host in situ extant life or evidence of past life. These include the RSLs on Mars and the plumes on Enceladus and Europa. While these are the most promising astrobiological targets, access to them is also the most restricted due to the desire to protect them from Earth derived contamination leading to either false positive detection of life or contamination of the exoplanet/exomoon ecosystem. In order to have missions access these regions, a higher level of sterilization is required. Canada should focus on development of sterilization techniques that would meet international requirements for access to these regions and thus potentially enable the first access to these most promising regions from an astrobiological perspective. It is anticipated that sterilization techniques and expertise developed could be applied to any of the proposed instrument focused investigations outlined above (e.g. micro-rover).

3.1.5.1 AB-04-01 Space Systems Development: Sterilisable Access to Special Regions

(Prioritization score: 83.3)

Development of sterilisable equipment/instrumentation that can be deployed to such regions including potentially sterile micro-rovers that can complete simple analyses and/or retrieve and return samples to larger rover/base of operations.

3.1.5.2 AB-04-02 Space Systems Development: Planetary Protection and Spacecraft Sterilization

(Prioritization score: 75.5)

As Mars missions move increasingly towards life detection, Mars Sample Return, and in the coming decades human missions to Mars, the issue of planetary protection becomes more relevant. Canadian scientists have relevant expertise and are interested in addressing the need to effectively achieve low bioloads on spacecraft to access Mars' Special Regions, intent on targeting regions with the highest likelihood of life, including determining the level and composition of contamination, and differentiating terrestrial life biosignatures from non-terrestrial signals. Canadian scientists and engineers could contribute to developing methods of sterilization of spacecraft and instruments. This work can be achieved via laboratory and analogue site studies, via experimentation stratospheric balloons, and in space via experiments on the ISS and CubeSats.

3.1.6 AB-05: Exoplanets: Characterization and Detection of Biosignatures

(Prioritization score: 76.0)

The discovery of thousands of potential and confirmed exoplanets in recent years, and the expected increases in this number with the coming launches of TESS and JWST have opened the door to extrasolar astrobiology.

Extrasolar planets can only be characterized via remote sensing, primarily via disk-integrated observations. This means that we can only hope to find extrasolar life on planets where it has significantly modified the surface and/or atmosphere in a detectable manner, as it has on Earth. Extrasolar Astrobiology is complementary to Solar System Astrobiology in three key ways:

(1) If an exoplanet exhibits signs of life, then it points to an independent genesis, as interstellar contamination is virtually impossible,

(2) there are exoplanets that are more similar to Earth than any extraterrestrial world in the Solar System, so if life is picky, then exoplanets are our best bet for extraterrestrial life, and

(3) there are vast numbers of exoplanets, enabling comparative planetology and, eventually, comparative biology.

The capability to characterize planetary atmospheres raises the potential to search for atmospheric biosignatures. The classic example is oxygen, which is only present in Earth's atmosphere at significant levels due to the photosynthetic activities of life. Unfortunately, oxygen has only been present in sufficient quantities to be remotely detectable for 10% of Earth's history. Developing robust biosignatures that are "in-band" for planned space telescopes is an area of active research.

A mission capable of directly imaging an Earth analog and looking for atmospheric biosignatures in its spectra will likely be able to monitor the brightness and color variations of the planet. The color variations of a pale blue dot allows one to infer the numbers, colors and locations of different surface types on the planet, as well as its obliquity. In fact, such observations are the only feasible way to know whether an exoplanet has liquid surface water, the definition of habitability. Moreover, the color variations of Earth betray not only its oceans but also its exposed continents, suggesting a planet with plate tectonics and hence long-term habitability. Finally, such methods could allow astronomers to identify surface biosignatures such as the red edge of chlorophyll.

We can only interpret a biosignature as such if we have a thorough understanding of possible *abiotic* atmospheric and surface signatures. Exoplanets provide great leverage for understanding the variety of planetary atmospheric and surface conditions. Since most exoplanets that we can study are not habitable in any global way, their atmospheric and surface character must be the result of abiotic processes. Only by studying a large number of diverse worlds can we hope to put the few temperate terrestrial planets in context.

The growing handful of terrestrial exoplanets with well-characterized masses and radii has bulk densities consistent with Earth-like iron/silicate composition. Meanwhile, observations of polluted white dwarfs indicate that all planets form from the same basic chemical building blocks. Continued studies of "dirty dwarfs" will help pin down the universal building blocks of planets and life.

By the late 2020's, the first ELTs will come online, including the TMT for which Canada is one of the principal partners. With their large collecting area and very high spectral resolution, these ground-based telescopes may be able to tease out the atmospheric signals of nearby temperate terrestrial planets orbiting nearby red dwarfs, including atmospheric biosignatures. It is likely that a flagship astrophysics mission launching in the 2030's will search nearby exoplanets for biosignatures.

(1) Science Approach

The only globally habitable planet in the solar system is Earth. The study of exoplanets allows us to estimate the frequency of such planets in the universe. Results from decades of ground-based radial velocity searches, as well as NASA's Kepler mission, suggest that planets are more plentiful and varied than one could have guessed based on the Solar System. The most common Earth-analogs (Earth-sized planets with Earth-like insolation) orbit red dwarf stars; these appear to be 10x more common than Earth twins (Earth analogs orbiting Sun-like stars). JWST will go a long way towards verifying whether the red dwarf variety of Earth analogs is truly habitable (i.e. do they have atmospheres, do those atmospheres have CO2 and/or H2O, etc.). If JWST data suggest that temperate terrestrial planets orbiting red dwarfs are, in fact, habitable, then we should consider a dedicated mission to search for biosignatures in their atmospheres. NASA's proposed LUVOIR mission is a likely candidate, as are the next generation of ground based telescopes, the ELTs.

We will have to wait until the 2030's for a space telescope that could search for biosignatures on dozens of terrestrial planets (NASA's LUVOIR and HabEx mission concepts). Nonetheless, NASA's WFIRST mission, to be launched in the mid-2020s, is currently baselined to have a coronagraph for direct imaging of nearby exoplanets. With a primary mirror of only 2.4 meters (same as Hubble), this mission will barely be capable of seeing the reflected light from hypothetical habitable rocky planets orbiting the nearest stars. However, it may be possible to launch a starshade to rendezvous with WFIRST at the end of the latter's primary mission. The Exo-Starshade (Exo-S) Science and Technology Definition Team (STDT) showed that such a combination would be capable of discovering and characterizing nearby habitable rocky planets [1]. The CSA should strongly support such a follow-on mission, which was estimated to cost $610M USD. This is the only credible path to exoplanet biosignatures in the next decade. A starshade allows simultaneous direct imaging over a broad wavelength range, enabling studies of exoplanet surfaces, including mapping oceans and vegetation.

3.1.6.1 AB-05-01: Space Observatory Investigation: Establish the Presence of Surface Liquid Water on an Exoplanet

(Prioritization score: 77.5)

There are two approaches to detecting water on a directly-imaged Earth analog.

(1) Water is shiny at glancing incidence, so one can detect glint (specular reflection) photometrically or polarimetrically. Directly imaging a planet at crescent phases requires a small inner working angle, necessitating a large aperture with an internal coronagraph, or a modest aperture coupled with an external starshade.

(2) Water is dark near nadir, so one can detect oceans via rotational mapping with multi-color photometry. This approach requires a large aperture, wide bandpasses (easier with a starshade) or multiple coronagraphs.

In either case, the requirements point towards a large space telescope with a high-performance coronagraph (~LUVOIR) or external starshade (~HabEx).

3.1.6.2 AB-05-02: Space Observatory Investigation: Establish the Presence of Biosignatures in an Exoplanet Atmosphere

(Prioritization score: 77)

For habitable planets orbiting red dwarfs, it is likely impossible to directly image the planet due to the small angular separation. However, these planets are more likely to transit their star, enabling transit and eclipse spectroscopy. The relevant biosignature molecules, notably oxygen (or ozone) and methane have absorption features in the optical and NIR. In principle, the JWST and ground-based ELTs should be able to search for biosignatures on these planets. If actual performance is not sufficiently good, then we may need a future NIR-MIR mission to search for biosignatures in the atmospheres of such planets. A LUVOIR-type mission might fit the bill.

For Earth analogs orbiting Sun-like stars, transits are improbable but it is feasible to directly-image the planet in the foreseeable future. A large aperture is required in order to obtain a high signal-to-noise spectrum in a reasonable integration time. Wavelength coverage well into the NIR is needed to detect multiple atmospheric biosignatures and to rule out geochemical and photochemical false positives. A mission like LUVOIR would be capable of searching for biosignatures for the nearest Earth twins.

Although missions capable of establishing exoplanet habitability and detecting exoplanet biosignatures are likely to be led by NASA due to their significant cost (>$5B), Canada is particularly well positioned to contribute instrumentation for high-precision photometry (MOST, BRITE), high-precision polarimetry (POMM), near-infrared spectroscopy (JWST/NIRISS, SPIRou, NIRPS), and direct imaging of exoplanets (GPI). Indeed, Canadian astronomers have already mooted the idea of contributing the coronagraph for the WFIRST mission and there are CSA representatives on the HabEx and LUVOIR STDTs. There is growing Canadian expertise in the characterization of exoplanet atmospheres and surfaces.

3.1.7 Astrobiology Roadmap

In the near term, the road forward for astrobiology in Canada needs to focus on two aspects:

(1) community building, and

(2) research prioritization.

Community building remains a key requirement for any research group, but particularly for the highly interdisciplinary and transdisciplinary research involved in astrobiology. A guiding structure needs to be developed to enable development and expansion of the astrobiology science community. This should include a central point for organization, coordination and collaboration, as well as to support interactions with national, industrial and IPs. The Canadian Astrobiology Network (CAN) was envisioned as such as nexus, but without funding support was not able to provide these functions, despite forging ties with NASA and other partners.

Research prioritization, that is the testing and selection of research priorities out of this document and/or new opportunities that are identified should be the second major focus. To achieve both of these objectives, the community would greatly benefit from the ability to hold meetings on an annual or biannual basis, perhaps ideally in conjunction with the other members of the planetary exploration community, such that there is an ongoing focus on targeting research and technology development most effectively. CSEW is an excellent venue for this, but occurs with limited frequency. A meeting, perhaps associated with another annual meeting such as Geological Association of Canada (GAC) - Mineralogical Association of Canada (MAC) or similar, could provide a venue for project and idea development. Complimentary to this would be supporting teleconference meetings amongst interested parties. The organization of these efforts could be led by the CAN or similar organization.

With respect to mission development, testing of the mission opportunities and identification of key priorities listed in this report should begin with initial funding of investigations that will identify the capability requirements and capacity required for potential mission ready systems. Upon completion of these initial studies, a selection process could be used to identify where follow up research should be focused and/or where new opportunities should be selected. This would be expected to occur over a two to three year timeframe.

A clear path-to-flight for science instruments should be established in order to engage science and technology partners and to effectively mature TRLs for promising instruments. We encourage funding activities at all stages: from science definition and requirement identification, to breadboarding and prototyping, to field testing.

Concurrent with these efforts, the CSA should fund the preparatory activities identified within this document such that the foundational knowledge and expertise are being developed for future mission development. The community would actively support a program similar to the previous Canadian Analogue Research Network (CARN) program, which funded a relatively large number of researchers at relatively modest levels, as an excellent tool to enable these preparatory activities. In addition to achieving preparatory activity research goals, such a program would have the added benefit of expanding interest in astrobiology and space science, while building capacity in industry and academia. This was demonstrated by the last CARN program which brought a number of researchers to astrobiology and space science due to the opportunities it presented. Similar programs also present the opportunity to highlight Canadian analogue sites and analytical expertise to researchers across the country and internationally. The CSA, through CARN and its previous efforts, was highly effective in building interest and research activity in astrobiology and space science. It can be expected that a renewed effort in this area would have similar results.

In the longer term, CSA should put in place a structure that would review the proposed investigations in this plan and determine which priorities show the most promise and whether new opportunities have been demonstrated via programs such as a renewed CARN program.

Other key other activities that would enable and achieve astrobiology research goal include: i) support for space data analysis; ii) support for participating scientists and co-investigators in planetary missions and instrument team members; iii) support for co-investigators in international projects: e.g. NASA Astrobiology teams, NASA Planetary Science and Technology from Analog Research (PSTAR), Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO), Maturation of Instruments for Solar System Exploration (MatISSE), ESA field-based programs, analyses of returned samples.; and iv) support for field-based analogue missions, including the involvement of astronauts in Mars mission scenarios.

3.1.8 Astrobiology Appendices

3.1.8.1 Canadian Involvement in Astrobiology-related Space Exploration Missions

3.1.8.1.1 Canadian Scientists Involved in the ESA ExoMars Trace Gas Orbiter and 2020 Rover Mission

Scientist	Affiliation	Representative
Allex Ellery	Carleton Univ	PanCam Instrument Team
Gordon Osinski	Univ. Western Ontario	PanCam Instrument Team
Edward Cloutis	Univ. of Winnipeg	ISEM Instrument Team
John Spray	Univ. of New Brunswick	CLUPI Instrument Team
Edward Cloutis	Univ. of Winnipeg	Ma_MISS Instrument Team
Lyle Whyte	McGill U	LSSWG Member
Jacek Kaminski	York Univ.	NOMAD Instrument Team
Jim Whiteway	York Univ.	NOMAD Instrument Team
Jack McConnell	York Univ.	NOMAD Instrument Team
Vicky Hipkin	CSA	ACS Instrument Team
Livio Tornabene	Univ. Western Ontario	CaSSIS Instrument Team

3.1.8.1.2 Canadian Scientists Involved in NASA Mars Science Laboratory Mission

Scientist	Affiliation	Representative
Ralf Gellert	Guelph U.	APXS Instrument PI
J.L. (Iain) Campbell	Guelph U.	APXS Instrument Team
John Spray	Univ. of New Brunswick	APXS Instrument Team
Lucy Thompson	Univ. of New Brunswick	APXS Instrument Team
Beverley Elliott	Univ. of New Brunswick	APXS Instrument Team
Richard Léveillé	McGill U.	Participating Scientist
John Moores	York U.	Participating Scientist
Mariek Schmidt	Brock U.	Participating Scientist
Ed Cloutis	Univ. of Winnipeg	Participating Scientist Collaborator

3.1.8.1.3 Canadian Scientists Involved in the NASA-ESA Cassini Mission

Scientist	Affiliation	Representative
Catherine Neish	Univ. Western Ontario	RADAR Team Associate Member

3.1.8.1.4 Canadian Scientists Involved in NASA Mars 2020 Mission

Scientist	Affiliation	Representative
Ed Cloutis	Univ. of Winnipeg	SuperCam Instrument Team Collaborator + MASTCAM-Z Instrument Co-investigator
Rebecca Ghent	U. Toronto	RIMFAX instrument Co-investigator
Christopher Herd	U. Alberta	Returned Sample Science Board Member
Richard Léveillé	McGill U.	SuperCam Instrument Team Collaborator

3.1.8.2 Current Astrobiology Projects

3.1.8.2.1 Canadian Scientists Involved in NASA Astrobiology Institute (NAI) Teams

Scientist	Affiliation	Representative
Richard Léveillé	McGill U.	SETI Team Collaborator
Wayne Pollard	McGill U.	SETI Team Collaborator
Lyle Whyte	McGill U.	Co-Investigator

3.1.8.2.2 CSA Flights and Fieldwork for the Advancement of Science and Technologies (FAST) Projects

Scientist	Affiliation	Representative
Greg Slater	McMaster U.	Detection and Assessment of Microbial Biosignatures in Basalts by UV Raman spectroscopy and Direct Analysis
Richard Léveillé	McGill U.	Astrobiology Training in Lava Tubes: ATiLT
Lyle Whyte	McGill U.	Development and testing of MICRO life detection platforms for planetary exploration in polar analogue sites
Alex Ellery	Carleton U.	
Ed Cloutis	Univ. of Winnipeg	High-Fidelity Rover Missions at Mars Analogue Sites

3.1.8.2.3 CSA Mars Sample Return Analogue Mission

Scientist	Affiliation	Representative
Gordon Osinski	Western U.	Mars Sample Return Analogue Mission Deployment
Lyle Whyte	McGill U.	MICRO life detection platforms for Mars Sample Return Protocols and Planetary Protection

3.1.9 References

- *3.1.2 AB-01: Biosignature Characterisation*

  [1] *Osinski G.R. Pierazzo E. 2012. Impact Cratering: Processes and Products. Wiley-Blackwell.*
  [2] *Heck, P.R., Schmitz, B., Bottke, W.F., Rout, S.S., Kita, N.T., Cronholm, A., Defouilloy, C., Dronov, A. and Terfelt, F., 2017. Rare meteorites common in the Ordovician period. Nature Astronomy, 1, 0035*
  [3] *Wilson L. 2009. Volcanism in the Solar System. Nat. Geosci. 2 389–397*
  [4] *Lopes et al. 2013*
  [5] *Head J.W. Mustard J.F. Kreslavsky M.A. Milliken R.E. Marchant D.R. 2003. Recent ice ages on Mars. Nature 426 797–802.*
  [6] *ISEC-G white paper*

- *3.1.5 AB-04: Accessing Special Regions*

  [1] *Seager et al. 2015*

- *3.1.6 AB-05: Exoplanets: Characterization and Detection of Biosignatures*

  [1] *Borovička J. Spurný P. Brown P.G. Wiegert P. Kalenda P. Clark D. Shrbený L. 2013. The trajectory structure and origin of the Chelyabinsk asteroidal impactor. Nature 503 235–237. doi:10.1038/nature12671*
  [2] *Popova O.P. Jenniskens P. Emel V. Kartashova A. Biryukov E. Khaibrakhmanov S. Shuvalov V. V. Rybnov Y. Dudorov A. Grokhovsky V.I. Badyukov D.D. Yin Q. Gural P.S. Albers J. Granvik M. Evers L.G. Kuiper J. Kharlamov V. Solovyov A. Rusakov Y.S. Korotkiy S. Serdyuk I. Korochantsev A. V Larionov M.Y. Glazachev D. Mayer A.E. Gisler G. Gladkovsky S. V Wimpenny J. Sanborn M.E. Yamakawa A. Verosub K.L. Rowland D.J. Roeske S. Botto N.W. Friedrich J.M. Zolensky M.E. Le L. Ross D. Li Q. Liu Y. Tang G. Hiroi T. Sears D. Weinstein I.A. 2013. RESEARCH ARTICLE Chelyabinsk Airburst Damage Assessment Meteorite Recovery and Characterization 342 1069–1073.*
  [3] *Bottke W.F. Morbidelli A. Jedicke R. 2002. Debiased orbital and absolute magnitude distribution of the near-Earth objects. Icarus 156 399–433. doi:10.1006/icar.2001.6788*
  [4] *Brown P.G. Assink J.D. Astiz L. Blaauw R. Boslough M.B. Borovička J. Brachet N. Brown D. Campbell-Brown M. Ceranna L. Cooke W.J. de Groot-Hedlin C. Drob D.P. Edwards W. Evers L.G. Garces M. Gill J. Hedlin M. Kingery A. Laske G. Le Pichon A. Mialle P. Moser D.E. Saffer A. Silber E. Smets P. Spalding R.E. Spurný P. Tagliaferri E. Uren D. Weryk R.J. Whitaker R. Krzeminski Z. 2013. A 500-kiloton airburst over Chelyabinsk and an enhanced hazard from small impactors. Nature 503 238–241. doi:10.1038/nature12741*
  [5] *Brown P.G. Spalding R.E. ReVelle D.O. Tagliaferri E. Worden S.P. 2002. The flux of small near-Earth objects colliding with the Earth. Nature 420 294–296.*
  [6] *Harris A.W. D'Abramo G. 2015. The population of near-earth asteroids. Icarus 257 302–312. doi:10.1016/j.icarus.2015.05.004*
  [7] *Rumpf C.M. Lewis H.G. Atkinson P.M. 2017. Asteroid impact effects and their immediate hazards for human populations. Geophys. Res. Lett. doi:10.1002/2017GL073191*
  [8] *Rumpf C.M. Lewis H.G. Atkinson P.M. 2017. Asteroid impact effects and their immediate hazards for human populations. Geophys. Res. Lett. doi:10.1002/2017GL073191*
  [9] *Boslough M.B. Brown P.G. Harris A.W. 2015. Updated Population and Risk Assessment for Airbursts from Near-Earth Objects (NEOs) in: IEEE Aerospace Conference. p. 12.*
  [10] *Tricarico P. 2016. The near-Earth asteroids population from two decades of observations. Icarus 284 19. doi:10.1016/j.icarus.2016.12.008*
  [11] *Plane J.M.C. 2012. Cosmic dust in the earth's atmosphere. Chem. Soc. Rev. 41 6507–18. doi:10.1039/c2cs35132c*
  [12] *Nesvorný D. Jenniskens P. Levison H.F. Bottke W.F. Vokrouhlický D. Gounelle M. 2010. Cometary Origin of the Zodiacal Cloud and Carbonaceous Micrometeorites. Implications for Hot Debris Disks. Astrophys. J. 713 816–836. doi:10.1088/0004-637X/713/2/816*
  [13] *Domokos A. Bell J. Brown P.G. Lemmon M. Suggs R. Vaubaillon J. Cooke W.J. 2007. Measurement of the meteoroid flux at Mars. Icarus 191 141–150. doi:10.1016/j.icarus.2007.04.017*
  [14] *Wiegert P. Brown P. Pokorny P. Lenartowicz K. and Krzeminski Z. (2017) Measuring the meteoroid environment of the planets with meteor detectors on Earth accepted to ApJ Letters May 28 2017*
  [15] *Poppe A.R. 2016. An improved model for interplanetary dust fluxes in the outer Solar System. Icarus 264 369–386. doi:10.1016/j.icarus.2015.10.001*
  [16] *National Research Council. Limiting Future Collision Risk to Spacecraft: An Assessment of NASA's Meteoroid and Orbital Debris Programs. National Academies Press 2011.*
  [17] *Brown P.G. Weryk R.J. Wong D. Jones J. 2008. A meteoroid stream survey using the Canadian Meteor Orbit RadarI. Methodology and radiant catalogue. Icarus 195 317–339. doi:10.1016/j.icarus.2007.12.002*
  [18] *Weryk R.J. Campbell-Brown M.D. Wiegert P. Brown P.G. Krzeminski Z. Musci R. 2013. The Canadian Automated Meteor Observatory (CAMO): System overview. Icarus 225 614–622. doi:10.1016/j.icarus.2013.04.025*
  [19] *Brown P.G. Weryk R.J. Kohut S. Edwards W.N. Krzemenski Z. 2010. Development of an All-Sky Video Meteor Network in Southern Ontario Canada: The ASGARD System. J. IMO 38 25–30.*

[20] *Alvarez L.W. Alvarez W. Asaro F. Michel H. V 1980. Extraterrestrial cause for the Cretaceous/Tertiary extinction. Science (80-.). 208 1095–1108.*

[21] *Grieve R.A.F. 2017. Logan Medallist 4. Large-Scale Impact and Earth History. Geosci. Canada; Vol. 44 Number 1 (2017)DO - 10.12789/geocanj.2017.44.113.*

[22] *Jourdan F. Renne P.R. Reimold W.U. 2009. An appraisal of the ages of terrestrial impact structures. Earth Planet. Sci. Lett. 286 1–13.*

[23] *Kring D.A. 1997. Air blast produced by the Meteor Crater impact event and a reconstruction of the affected environment. Meteorit. Planet. Sci. 32 517.*

[24] *Schulte P. Alegret L. Arenillas I. Arz J.A. Barton P.J. Bown P.R. Bralower T.J. Christeson G.L. Claeys P. Cockell C.S. Collins G.S. Deutsch A. Goldin T.J. Goto K. Grajales-Nishimura J.M. Grieve R.A.F. Gulick S.P.S. Johnson K.R. Kiessling W. Koeberl C. Kring D.A. MacLeod K.G. Matsui T. Melosh J. Montanari A. Morgan J. V Neal C.R. Nichols D.J. Norris R.D. Pierazzo E. Ravizza G. Rebolledo-Vieyra M. Reimold W.U. Robin E. Salge T. Speijer R.P. Sweet A.R. Urrutia-Fucugauchi J. Vajda V. Whalen M.T. Willumsen P.S. 2010. The Chicxulub asteroid impact and mass extinction at the Cretaceous-Paleogene boundary. Science (80-.). 327 1214–1218. doi:10.1126/science.1177265*

3.2 Planetary Atmospheres

Community Report from the Planetary Exploration Topical Team on Planetary Atmospheres

Table 3-2 Planetary Exploration - Planetary Atmospheres Topical Team

Name	Affiliation
John Moores (Chair)	York University
Christina L. Smith, Executive Secretary	York University
Eric Choi Executive Secretary	University of Waterloo
James A. Whiteway	York University
Kimberly Strong	University of Toronto
Kaley A. Walker	University of Toronto
James R. Drummond	Dalhousie University
Edward Cloutis	University of Winnipeg
Michael G. Daly	York University
Carlos F. Lange	University of Alberta
Craig Haley	Com Dev Ltd.
Warren Soh	Magellan Aerospace
Kevin Olsen	University of Toronto
Frédéric Grandmont	ABB Inc.
George Nikolakakos	York University
Ray Jayawardhana	York University
William Ward	University of New Brunswick
Cameron Dickinson	MacDonald Dettwiler and Associates
Barbara Sherwood Lollar	University of Toronto

3.2.1 Introduction to Planetary Atmospheres in Canada

The exploration of planetary atmospheres is an area in which Canada has a proven expertise. This has included building cutting-edge instrumentation, such as the LiDAR and meteorological instruments to investigate the Martian Atmosphere as Canada's contribution to the 2008 Phoenix Mission. Canada has also developed advanced techniques to investigate the atmospheres of other planets from orbit, such as the Mars Atmospheric Trace Molecule Occultation Spectrometer (MATMOS) concept. Canadian scientists also support atmospheric studies in their involvement with contributions to NASA's Mars Science Laboratory (MSL) and ESA's Mars Trace Gas Orbiter (TGO) missions. Finally, with new experimental facilities being developed, such as the Canadian Planetary Simulator (CAPS), Canada has demonstrated a commitment to laboratory studies at home which enhance the value of data returned from spacecraft by testing theories and providing context for those measurements.

These past and ongoing studies encompass a wide range of topics. The examination of trace molecular constituents of atmospheres can elucidate past and present processes occurring on planetary bodies, shedding light on their evolution. The atmosphere also can affect the surface and vice-versa, hence the strong interest and activity in understanding atmosphere-surface interactions that permit the presence of liquids on terrestrial planets and weather planetary surfaces. Understanding the dynamics of planetary atmospheres reveals the movement of materials from one place to another across planetary surfaces and allows for the development of more advanced computer models of winds that may be applied to weather forecasting on the Earth. Lastly, aerosols – whether generated through photochemistry high in the atmosphere, condensing out of molecular precursors when conditions are right, or lofted from the surface can have an outsized effect on the preceding three processes. Aerosols affect the energy balance of an atmosphere and provide abundant surfaces for molecular chemistry to occur.

As the Canadian planetary atmospheres community looks to the future, there is a strong interest in expanding our activities to explore the atmospheres of other planets as well as Mars. Many of the same techniques developed over the past 20 years can be extended to provide information on the atmospheres of Venus, Titan, Pluto and the Giant Planets. As well, the growing interest in studying mineral dusts and the exospheres of so-called airless bodies is clear from aerosol studies being conducted as a part of other missions. Finally, there is a desire to coordinate the activities of those exploring the atmospheres of our own solar system with the burgeoning field of exoplanetary research. Here, advanced knowledge of our own solar system obtained by planetary spacecraft serves as a 'Local Laboratory' that can be used to interpret the data being returned from other solar systems by telescopic investigations.

As such, the Planetary Atmospheres TT has identified a total of four objectives for future Canadian Space Exploration. This list has been prioritized as is as follows:

- PAT-01 Understand Mars Surface-Atmosphere Interactions (77.5)
- PAT-02 Understand the Chemistry of Planetary Atmospheres (77.5)
- PAT-03 Constrain the Dynamics of Planetary Atmospheres (60)
- PAT-04 Understand Atmospheric and Exospheric Aerosols (53)

3.2.2 PAT-01: Understand Mars Surface-Atmosphere Interactions

Major discoveries during the NASA Phoenix Mars mission included the confirmation of water ice below the surface [1], observation of water ice precipitation to the surface [2], and the identification of perchlorate in the surface regolith [3]. More recently, the NASA Curiosity Rover detected the presence of perchlorate in Gale Crater [4], suggesting that it is globally distributed. Perchlorate salts are of great interest for studies of Mars due to their ability to absorb water vapour and form a liquid brine (deliquescence) as well as an ability to greatly depress the freezing point of water when in solution. Subsequent laboratory studies have demonstrated that deliquescence on Perchlorate salts can form liquid water solutions in the environmental conditions on Mars ([5]; [6]). The dark streaks on surface slopes, referred to as RSLs, that are observed on Mars have recently been interpreted as flowing water. One of the leading hypotheses for the source of liquid water is atmospheric humidity by deliquescence of perchlorate salts ([7]; [8]). This has intriguing biological implications since liquid brines could potentially provide a habitable environment for living organisms [9]. Additionally, it has been speculated that these salts may play a significant role in the hydrological cycle and the geological history of water on Mars. Thus, the investigation of the mechanisms of water exchange at the surface of Mars is potentially of the highest impact.

The study of the processes that lead to wetting of the surface as manifested in RSL features is one of the highest priority science objectives for the next Mars orbiter in the NASA Next Orbiter Science Analysis Group (NEX-SAG) report:

> *NASA NEX-SAG Repor.t, Objective S-B: Characterization and understanding of dynamic modern surface processes, especially the possible brine flows suggested by the observation of Recurring Slope Lineae (RSL).*

The objective is central to planetary science and new knowledge can be anticipated to stimulate funding for a new series of missions. The scientific results concerning habitability on Mars would be of very high impact to planetary science.

This endeavour would require the development of techniques and instruments that have yet to be applied in planetary missions. These instruments would be based on the heritage of Canadian contributions to previous missions (e.g. the LiDAR instrument on the NASA Phoenix mission). The results would cut across several disciplines including atmospheric science, geology, and biology.

This objective involves recent Canadian high impact research and facilities.

- For example, the Canadian leadership with the LiDAR and meteorological instruments on the NASA Phoenix mission (e.g. [2]) and also recent high impact publication of results from laboratory investigations (e.g. [5]).

Canada has a strong potential to lead significant contributions.

- For example, recent developments for surface water investigation with Raman LiDAR based on the heritage of the LiDAR instrument on the Phoenix mission [5].

Results concerning water on the surface of Mars and the implications for biological habitability are regularly reported in international media.

- For example, the announcement of the discovery of water ice precipitation with the Canadian LiDAR instrument on the NASA Phoenix Mars mission was one of the top international news stories during September 2008. This discovery has also been cited as part of the third most important discovery in the top ten list of the NASA Mars Exploration Program Analysis Group (MEPAG 2011). More recent investigations of the sources of water for RSL are currently receiving significant international media attention.

This high impact objective would draw international talent. The trained HQP would gain skills in optical technologies that are of widespread use in Canadian science and industry. The optical technologies developed for investigation of the surface of Mars have commercial applicability as evidenced in the success of Canadian industry in the areas of laser and passive remote sensing.

3.2.2.1 PAT-01-01: Preparatory Research: Laboratory Chamber Experiments

(Rank #1 70.9/100)

Laboratory chamber experiments serve to advance measurement techniques and the scientific investigation of the processes that are involved in the exchange of water between the surface and atmosphere of Mars. This work has commenced for Raman LiDAR studies of water exchange at the surface of Mars and the first results have been published [5]. It was demonstrated that Raman scattering measurements are capable of detecting the deposition of water and discriminating between the processes of direct deposition (frost), deliquescence by Perchlorate salts, and adsorption on regolith grains.

Laboratory Studies are ongoing with a Mars Chamber at York U. to determine the optimal instrument design for laser remote sensing (e.g. LiDAR) of the surface of Mars during a landed Mars mission. Important issues to be addressed include the following.

a) Development of a Method for Quantifying Water Uptake **(Rank #2 61.1/100)**

A method will be devised to quantify the mass of water deposited per unit area using measurements from the Mars Raman LiDAR. This will require a means for calibrating the measurement, such as comparison with Raman scattering from a known target.

b) Laser wavelength **(Rank #3 60.6/100)**

Experimental studies are required to determine the optimal laser wavelength. Challenges include light absorption by the regolith material at UV wavelengths, interference in the detection of Raman scattering due to fluorescence at visible wavelengths, and the detector efficiency at IR wavelengths.

c) Determination of the laser pulse energy and the minimum Raman power-aperture product

(Rank #4 56.9/100)

The required laser pulse energy must be determined for a given stand-off distance. This is vital since there will be a limitation on the amount of power consumed by the laser.

d) Technique for the detection of the Raman Scattering spectrum **(Rank #5 56.2/100)**

There is a trade-off between various methods. For example, use of interference filters with a single photomultiplier detector would provide a straightforward, reliable approach with the best detector sensitivity and would be closest in design to the LiDAR on the Phoenix mission. A grating spectrometer with an array detector would provide the advantage of measuring the complete spectrum of Raman scattering with each laser pulse, resulting in a smaller power consumption, but would likely require greater mass and volume.

3.2.2.2 PAT-01-02: Instrument Investigation: SWIRL: Surface Water Investigation with Raman LiDAR on Mars

(Rank #1 76.1/100)

- This would also include capability to determine the composition of atmospheric aerosols and water content in clouds and precipitation. **(Rank #2 67.2/100)**

This instrument has been demonstrated in laboratory studies based on a chamber for simulation of Mars surface conditions [5]. The long term goal is for an instrument contributed to a landed Mars mission. The instrument would provide measurements of the Raman scattering of laser light from the surface in order to identify the processes that are involved in the deposition of water on the surface. Laboratory investigations have demonstrated that the method is capable of detecting the deposition of water by Perchlorate deliquescence, adsorption on regolith grains, and frost formation. It would also provide atmospheric measurements that advance on the LiDAR instrument from the Phoenix Mars Mission by applying Raman scattering to assess the composition of atmospheric aerosol and the ice water content in clouds and precipitation.

The most vital complementary measurements to SWIRL would be as follows.

a) Surface Temperature **(Rank #1 64.9/100)**

This could be provided by measurement of the flux of IR radiation emitted from the surface.

b) Atmospheric temperature **(Rank #2 59.8/100)**

This would follow from the MET measurement package on the Phoenix Mars Lander that was supplied by CSA.

c) Atmospheric water vapour **(Rank #3 58.3/100)**

The most straightforward instrument would make use of a capacitive sensor similar to the one that was part of the Thermal and Electrical Conductivity Probe (TECP) package on the Phoenix Mars mission. A faster response time would be of value, and this could be achieved with a tuneable diode laser absorption spectrometer.

3.2.2.3 PAT-01-03: Data Analysis Investigation: Modeling studies to determine the global distribution of water exchange

(Rank #3 61.3/100)

Modeling studies are desired to determine the global distribution of water exchange based upon experimental results and combined with existing measurements of surface and atmospheric parameters at Mars from Spacecraft. This includes retrievals from orbit of atmospheric pressure and temperature, water ice cloud thickness and extent as well as evidence for hydration at the surface, such as RSL.

3.2.2.4 PAT-01-04: Preparatory Research: Analysis of Raman LiDAR measurements to determine how the Raman signal is affected by the quantity of water uptake

(Rank #4 59.4/100)

and by the form that water takes including ice, brines and adsorbate

(Rank #5 58.6/100)

The Laser Raman scattering measurements by the SWIRL instrument would produce data products files that are similar to what was generated by the LiDAR instrument on the Phoenix Mars mission (e.g. [2]). The detected signal corresponding to Raman scattering as a function of range near to the lander would be recorded at specific wavelengths. The Raman LiDAR would be pointed at the surface of Mars in front of a lander. The measurements would be carried out in the evening as the sun is setting and the surface temperature is decreasing. The signal strength at wavelengths corresponding to Raman scattering from water in its various forms (e.g. adsorbed, liquid Perchlorate solution, ice) would indicate how the water is being taken up on the surface and the amount.

3.2.2.5 Summary for Objective PAT-01

3.2.2.5.1 Canadian Science Roadmap

The following investigations would be required for the advancement of instrument development and scientific analysis.

a) **Laboratory Chamber Experiments for Scientific Investigation**

Experiments using a chamber to simulate the conditions on the surface of Mars will provide a means for determining the processes that are expected to be relevant for the exchange of water between the atmosphere and surface on Mars. This will provide a basis for the scientific requirements. The work is ongoing at York U. (e.g. [5]).

b) **Laboratory Chamber Experiments for Instrument Development**

The requirements on the instrument design for providing the measurements that address the scientific requirements will be determined from laboratory experiments with a chamber that simulates the environmental conditions at the surface of Mars. This work will be carried out using the new CAPS facility at York U.

c) **Numerical modelling studies**

Simulations with a Mars General Circulation Model (GCM) will provide a global perspective on the environmental conditions on the surface of Mars. This will provide an assessment of the regions that are most relevant for study of the exchange of water between the atmosphere and surface. The simulations also provide a valuable tool in the scientific analysis that will assess the impact of the exchange of water at the surface on the hydrological cycle and geological history of water on Mars.

3.2.2.5.2 Canadian Science Capacity

The study of water exchange on the surface of Mars builds upon the scientific capacity that was created from the Canadian participation in the Phoenix Mars mission. This includes the implementation of the Phoenix LiDAR and meteorological instruments, and the scientific analysis of the measurement data (e.g. [10]; [2]). The Canadian Science Team for the Phoenix mission was led from York U. with participation from the U. of Alberta and Dalhousie U. The Canadian capacity built as a result of the Phoenix mission also includes numerical modelling [11] and laboratory experiments [5]. A new capacity is the CAPS facility, including a new chamber, and this is currently under construction at York U. with substantial funding from the CFI.

3.2.2.5.3 Enabling Canadian Technologies

The SWIRL investigation/instrument would be based on the same technology that was employed for the LiDAR instrument on the Phoenix Mars mission. This was based on three decades of LiDAR based scientific research at York U., the commercial development of LiDAR technology at Optech Inc. (Vaughan, ON), and the prime contractor was MDA Space Missions (Brampton, ON). The SWIRL investigation would be led by the same academic and industry partners.

3.2.3 PAT-02: Understand the Chemistry of Planetary Atmospheres

The chemistry and dynamics of planetary (and planet-like) atmospheres are important subjects of continuing study. The Earth's atmosphere is the one that we currently understand the best, but it is clearly only one in a large spectrum of possible atmospheres. The solar system provides other examples for study such as: Mars, Venus, Titan, Pluto and moons of gas giants as well as the gas giants themselves.

The chemistry of these atmospheres is likely to be very diverse and complex because of the differing radiative and dynamic properties and histories of the various celestial bodies. Understanding more atmospheres will provide insight into the more general topic of planetary atmospheres with application to the Earth, the Solar System and exoplanets. In addition, understanding of planetary atmospheres within the Solar System will shed light on the evolution of the Solar System and how it came to be in its present state.

The atmosphere of Mars is of special merit within the Solar System because it is not only of scientific interest but also of practical interest with the hope of eventually having a human on Mars. To accomplish this, the spacecraft must travel successfully through the atmosphere and once on the surface, the humans must survive in the environment. This is a very practical problem with high motivation to provide a more complete understanding of the situation.

The final issue is that of life, current or in the past, in the Solar System. This is a complex question that will need to be addressed over the long term. These studies will include markers for biogenic and geological activity that will provide essential information for this topic.

Initial missions will be “discovery” in the sense that we do not know much about the composition of these atmospheres compared to Earth. These will be followed by investigative missions probing specific aspects of the chemistry, and these will proceed in tandem with missions to understand the dynamics.

In combination with the space missions, a modelling effort must be instituted to interpret the measurements obtained both in the local context of the celestial body being studied and in the broader context of planetary atmospheres in general. For instance, detailed modelling of the composition of the atmosphere of Titan and of outgassing from icy moons of Jupiter and Saturn has not yet been done.

Canada has a lead in FTSs and earth observation techniques. Instruments developed to examine the composition of the atmospheres of Earth and other planets have been spun off into earth-observing instruments for commercial satellites, commercial ground-based instruments, and international government satellites. This would be an opportunity to expand those techniques to the planets.

3.2.3.1 Preparatory Research

Canada is a world leader in FTS technology for making observations of atmospheric composition. An orbital FTS operating in solar occultation mode (making observations of the solar disk through the limb of the atmosphere) benefits from a very long optical path length, very high signal-to-noise, fine vertical resolution, and is self-calibrating. The CSA uses this technique in its Earth-observing Atmospheric Chemistry Experiment (ACE) FTS on SCISAT, and intended to apply the technique to studying the Martian atmosphere as part of the ExoMars TGO mission. This investigation is an extension of those two missions: to prepare a high-resolution spectrometer for a future planetary mission, such as reviving the instrument intended for ExoMars for a future Mars mission of opportunity, or adapting the technology for another target, such as Titan, or an out-gassing icy moon of Saturn or Jupiter.

The FTS technique is highly versatile, and has been used in Canada in laboratories, ground-based observatories, balloon and airplane flights, and satellite missions. It can be adapted to be used in a variety of observation geometries, such as nadir-pointing. Depending on the target body, the wavelength region needed and the scientific objectives, a different spectrometry technique may be required, such as that deployed on the Nozomi spacecraft to study the upper atmosphere plasma environment of the Mars atmosphere, or the dual grating diode spectrometers used by the Measurements of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation (MAESTRO) instrument on SCISAT to record spectra with visible and ultra-violet wavelengths.

Preparatory research for such a mission would include several distinct, but related tasks that have been undertaken by Canadian research groups to support the Nozomi and ExoMars missions to Mars. These include those described in sections 3.2.3.1.1 through 3.2.3.1.3.

3.2.3.1.1 PAT-02-01: Preparatory Research: Developing Mars general circulation models to study temperature, pressure and gas chemistry

(Rank #1 66.7/100)

Furthering our understanding of the Mars atmosphere requires general circulation models including chemistry to be developed and tested with data collected by past and future missions. These models will allow investigations to be undertaken and scenarios for new missions to be tested. A GCM combines measurements of the physical state of the atmosphere (temperature, pressure, dust opacity, cloud coverage) and the abundance of constituent gases. The model computes the transport of air parcels at variable scales constrained by the measurements made by orbiting spacecraft and ground-based observatories. This is used to extrapolate sparse measurements of gas abundance to global or regional coverage, thus allowing the mapping of trace gas distribution. This can also help provide more accurate estimates of relative fractions between gases, which is necessary to measure chemical reaction rates between species. These are critical goals of current and future missions to understand the nature of any trace gases diagnostic of active geological or biological activity. In preparation for a CSA contributed instrument for the ESA/Roscosmos ExoMars TGO, work was done to adapt the Canadian Global Environmental Multiscale Model (GEM) GCM for use on Mars. This work continues to support ESA's NOMAD instrument on the TGO ([1]; [2]).

3.2.3.1.2 PAT-02-02: Preparatory Research: Refine data analysis algorithms and software for orbital Mars spectrometer missions

(Rank #2 54.2/100)

Much work has been done on algorithms and software development for Earth missions but each mission has unique objectives. For a Mars mission, the available data bandwidth is low and so the division between on board processing and ground-based processing may have to be completely different from that for Earth observation. Using on-board processing is less flexible and so more care has to be taken to ensure resilience against unexpected events, both engineering and scientific. The data that are transmitted to Earth must be of the highest scientific value, and this may change over the course of the mission as understanding is gained.

At a more fundamental level, the balance of gases and aerosols is quite different in the Martian atmosphere. The measurements objectives are also different and so, even well proven existing algorithms will need to be adapted.

3.2.3.1.3 PAT-02-03: Preparatory Research: Refine spectroscopic parameters using laboratory measurements

(Rank #3 53.9/100)

There has been a large effort to improve spectroscopic parameters in the last several decades. However, much of the detailed information obtained is more relevant to Earth than to other atmospheres within the solar system. Efforts to extend these measurements to the pressures and lower temperatures expected in other atmospheres are needed. In addition, the gases and ro-vibrational and electronic spectral bands of interest will change depending upon the target, thus needing further work.

Instrument Development for Space

Canada is a world leader in FTS technology for making observations of atmospheric composition. The CSA uses this technique in its Earth-observing ACE-FTS on SCISAT and intended to apply the technique to studying the Martian atmosphere as part of the ExoMars TGO mission. This investigation is an extension of those two missions: to prepare a high-resolution spectrometer for a future planetary mission such as reviving the instrument intended for ExoMars for a future Mars mission of opportunity or adapting the technology for another target such as Titan or an out-gassing icy moon of Saturn or Jupiter. The FTS technique is highly versatile and has been used in Canada in laboratories ground-based observatories balloon and airplane flights and satellite missions. It can be adapted to be used in a variety of observation geometries such as nadir-pointing. Depending on the qualities of the target body and the scientific objectives a different spectrometry technique may be employed such as that deployed on the Nozomi spacecraft to study the upper atmosphere plasma environment of the Mars atmosphere or that used by the Measurements of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation (MAESTRO) instrument on SCISAT to record spectra with ultra-violet wavelengths.

The instrument development described in sections 3.2.3.2 through 3.2.3.7 are a result of the Preparatory Research defined in section 3.2.3.1.

3.2.3.2 PAT-02-04: Space System Development: Develop leading Fourier Transform Technology for ground and space applications

(Rank #1 67.3/100)

A future, next-generation FTS, such as for investigating trace gases diagnostic of active biogenic or geological processes in the Martian atmosphere, would have to be capable of resolving individual spectral lines, have a broad spectral range, high signal-to-noise ratio (SNR), and fine vertical resolution. Engineering requirements would include constraints on physical size, power consumption, and data return rate. These requirements are already achievable with current Canadian technology, having been developed for ACE-FTS and ExoMars. By viewing the sun directly, we receive a very high input signal, reducing SNR, which enables identification of very weak spectral signatures due to target trace gases. The solar occultation geometry makes measurements throughout the vertical limb of the atmosphere, with spacing between 1.5 and 5.5 km, providing sensitive measurements at all altitudes with much finer vertical resolution than a nadir-viewing instrument. This allows us to investigate the vertical distribution of trace gases.

A compact FTS, such as ACE-FTS, is capable of a spectral resolution of 0.02 cm^{-1}, which is fine enough to resolve individual spectral features. Such a resolution is necessary to separate weak absorption features from stronger features produced by more abundant gases. An FTS has a broad spectral range, enabling detection of many gases with each measurement. The instrument is readily adaptable to other missions. Smaller form-factor versions, with lower spectral resolution have already been developed. A portable instrument has been developed and used in balloon missions and for Arctic research. A version of the instrument has also been used in nadir viewing mode (Greenhouse Gases Observing Satellite (GOSAT)) by JAXA using a Canadian built interferometer.

3.2.3.3 PAT-02-05: Space System Development: Develop small-scale spectrometer technology for intermediate applications

(Rank #2 63.8/100)

Non-FTS technologies are also a Canadian hallmark and can be used in small form-factors on medium-sized spacecraft in situations that do not demand the resolution of an FTS, or on missions where spectral support is advantageous, but not a key payload driver.

3.2.3.4 PAT-02-06: Space System Development: Develop small solar occultation/limb/nadir spectrometers/imagers for Nanosatelite applications

(Rank #3 59.1/100)

For the smallest applications, such as on small daughtercraft deployed in support of planetary spacecraft, specialty devices are needed. In these applications, aperture, mass and power are all extremely limited. However, the ability to simultaneously examine the atmosphere from several perspectives makes constellations of such small craft attractive.

3.2.3.5 PAT-02-07: Space System Development: Develop Canadian-led small satellite systems

(Rank #1 71.5/100)

Canada has the potential to lead in this area and should develop daughtercraft platforms for planetary exploration. Working within this new form-factor will necessitate new instrument development. For instance, a new telescope was also under development to optimize light collection for a Martian orbit with a lower altitude and smaller visible solar disk, and also to reduce the size of FTS systems.

3.2.3.6 PAT-02-08: Space System Development: Develop fully remote systems (optics, detectors, coolers, power systems, buses, etc.)

(Rank #2 70.4/100)

Many small spacecraft instruments will place substantial requirements on the platform and its subsystems. In particular, the requirements for certain spectroscopic systems require cooling systems that are currently too large for the small satellite form-factor. As such, systems will operate far from the main spacecraft. It would be advantageous to make them as autonomous as possible.

3.2.3.7 PAT-02-09: Space System Development: Develop on-orbit data processing software and hardware

(Rank #3 59.1/100)

Since data rates will be low from small satellites deployed from spacecraft, the ability to perform data processing on-orbit either on the daughtercraft or parentcraft before transmission to Earth has the potential to save substantial downlink capacity.

Instrument Investigations

The science measurements described in sections 3.2.3.8 through 3.2.3.13 are desired to achieve Objective PAT-02.

3.2.3.8 PAT-02-10: Instrument investigation: Measure the isotopic fractionation of water and HDO in the atmosphere of Mars to better than 100 pptv and examine the distribution and variability of HDO

(Rank #1 61.8/100)

The deuterium-to-hydrogen (D/H) ratio is a key parameter in understanding the escape of hydrogen, and by extension water, from the Martian system since it is enriched compared to Earth. Current estimates for the hydrogen-deuterium oxide (HDO) abundance are approximately 1 part in 1000. Making accurate measurements to a higher precision than this can lead to refining our estimate for the D/H ratio to better than 1%. These measurements will also help us better understand the water cycle on Mars by examining the vertical distribution of water and HDO and refining measurements of diurnal and seasonal water transport. There is also unique physics in the HDO cycle that needs to be examined. Isotopic fractionation has been shown to occur at condensation, leading to atmospheric water vapor being depleted in deuterium compared to ice in the polar caps. This study would help constrain both the water cycle and HDO cycle.

3.2.3.9 PAT-02-11: Instrument investigation: Aim to measure vertical profiles of methane and other hydrocarbons (ethane, ethylene) in the Martian atmosphere with a precision of better than 1 ppbv

(Rank #2 61.8/100)

The hydrocarbon chemistry of Mars is poorly understood. It is known that methane can be produced through both biotic and abiotic processes, but the pathway leading to the creation of methane and its eventual destruction is poorly understood. A dedicated search to determine, unambiguously, the existence of methane is needed. Then it must be followed by a search for other hydrocarbons associated with methane chemical cycles. The relative of abundance of ethane, ethylene, or formaldehyde can help determine whether a methane source is biotic in origin or not. Finally, we need to constrain the oxidative state of the Martian atmosphere, which may be an important methane gas-phase loss mechanism. This can be done by making simultaneous measurements of methane, water vapour, and NO2 and HO2, whose abundance constrains the OH production rate.

3.2.3.10 PAT-02-12: Instrument investigation: Measure and compare abundances of isotopologues of carbon dioxide and methane (to 1 pptv) in the Martian atmosphere to inform the source of methane

(Rank #3 61.3/100)

Understanding the isotopic composition of Mars's methane as well as its variability at the pptv level may inform the ultimate sources and sinks of this molecule. For instance, Carbon-13 is associated with biogenic sources and sinks, whereas higher abundances of Carbon-12 are associated with abiotic processes. Canadian scientists are already world leaders in understanding carbon isotope fractionation and methane sources on Earth. This requires very high resolution and signal, such as those provided by the MATMOS investigation.

3.2.3.11 PAT-02-13: Instrument investigation: Detect sulphur-bearing molecules in the atmosphere of Mars to a sensitivity of better than 1 pptv

(Rank #4 59.0/100)

Sulfur-bearing compounds can provide helpful information on past, and perhaps recent, volcanism on Mars. Currently, no sulfur-bearing gas species have been detected in the atmosphere of Mars. Their existence is important to constrain since active volcanism may be a source of methane, and identifying and quantifying sulfur species will lead to a constraint on a biological source of methane. This would also help us to understand the volcanic past of Mars.

3.2.3.12 PAT-02-14: Instrument investigation: Measure the composition of tenuous atmospheres of icy moons, searching for hydrocarbons

(Rank #5 53.6/100)

While the interior oceans of icy moons may be habitable, it is not well known whether they are inhabited. Understanding the hydrocarbon chemistry of material released through plumes, which forms tenuous atmospheres, may be helpful in understanding these hidden environments. Plumes of water have been regularly observed at Enceladus, and recently confirmed at Europa. While a mission to the interior of these moons is far off, detailed remote sensing studies of the composition of the plume ejecta can provide unprecedented insights into the composition and habitability of the liquid water sub-surfaces.

3.2.3.13 PAT-02-15: Instrument investigation: Detect chlorine-bearing molecules in the atmosphere of Mars with a sensitivity of better than 100 pptv

(Rank #6 53.1/100)

Energetic processes in the Martian atmosphere are thought to be important to the creation of the perchlorate molecules which can compose up to 1% by weight of surface materials. These super-oxides are critical to understanding the Martian water cycle, through deliquescence and thereby may have a significant role in the production and maintenance of RSL. These compounds could be a source of metabolic energy for biological systems and for abiotic chemical processes. The measurement of HCl can also provide insight into the oxidative power of the Mars atmosphere and possible loss mechanisms of methane. Finally, HCl, like any sulfur-bearing species, will lead to an improved understanding of volcanic activity in the distant or recent past.

3.2.4 Secondary Payloads

The instrument investigations described in sections 3.2.3.8 through 3.2.3.13 may be contributed to by CubeSat class missions defined in sections 3.2.4.1 through 3.2.4.3.

3.2.4.1 PAT-02-16: Secondary payloads: Develop small-scale versions of primary instruments as secondary instruments for flagship-class missions

(Rank #1 71.0/100)

In understanding atmospheric processes, additional perspectives can be useful. However, it is not always possible to deploy several large instruments. Instead, a large and highly capable instrument (for instance, an FTS) which serves as the primary payload on a mission could be assisted by simpler spectrometers with lower resolutions deployed on CubeSat-class daughtercraft.

3.2.4.2 PAT-02-17: Secondary payloads: Develop low-mass, low-power versions of existing instruments

(Rank #2 69.4/100)

In order for spectrometers to fit within the constraints of small CubeSat-class secondary payloads, low-mass and low-power versions of existing instruments must be developed.

3.2.4.3 PAT-02-18: Secondary payloads: Develop solar imaging technology

(Rank #3 55.1/100)

Because of the aperture limits of small secondary CubeSat-class spacecraft, applications in which the photon-density is high (e.g. occultation) are particularly well suited to such small platforms and should be prioritized.

3.2.4.4 PAT-02-19: Astronaut-led Investigation: Man-portable FTS for Earth-Observation: Deploy existing Canadian sun photometer or FTS technology on ISS

(Rank #1 71.1/100)

In Canada, there is already interest in sending a portable spectrometer to the ISS to be operated by a Canadian astronaut. Previous missions have already done so: Environment Canada Sun photometers were carried on STS-41G by Marc Garneau [1] and STS-52 by Steven MacLean [2]. Recent interest has been driven by the availability of an interferometer: the ExoMars Engineering Demonstration Unit, delivered to the CSA by ABB-Bomem. Furthermore, a portable version of this interferometer already exists at the U. of Toronto. Due to the size and weight of this instrument, an instrument to be operated by an astronaut could also be derived from the already-developed, compact version.

A mission would involve installation on the space station (one sortie), followed by automatic operation with data analysis performed on the ground. The feasibility of the ISS as a platform for Earth-observation has been demonstrated by NASA's Stratospheric Aerosol and Gas Experiment (SAGE) III on ISS mission. The main benefit to placing a spectrometer on the ISS instead of a dedicated spacecraft is reduced cost and system simplicity. However, the ISS orbit restricts the area covered by the instrument (SCISAT is in a high-inclination orbit, which provides near-global coverage).

3.2.4.5 Summary for Objective PAT-02

3.2.4.5.1 Canadian Science Roadmap

As Canada has contributed planetary instruments for spacecraft developed by International Partners through international competitions, the first task will be to produce a successful Canadian FTS proposal for an international Announcement of Opportunity (AO). Of primary interest to the Canadian community is a follow-up mission to Mars, such as the announced NASA 2022 telecommunications orbiter. This is because a Canadian-led FTS instrument was successfully selected for the ExoMars mission (withdrawn following NASA's termination of participation), and significant technology development has already been undertaken, which will strengthen a follow-up proposal. Other targets (e.g. moons of Saturn or Jupiter) are of equal, or greater, interest to the Canadian community, but an AO is not immediately anticipated.

Immediate research needed following an AO will include performing feasibility and sensitivity studies to estimate the design requirements needed to achieve prescribed scientific objectives, and to demonstrate that the technique will be viable at the target planet. After selection, key technologies will need to be prepared to meet the design requirements (see Sect. 3.2.3.5). A version 1 of the analysis software will need to be prepared prior to commencement, and evaluated with simulated data. Extensive modelling studies will also need to be performed in preparation for making observations. Once science operations commence, a team will be responsible for data processing and quality control to produce trace gas volume mixing ratio vertical profiles, which will be analyzed by a diverse team of academic researchers to deduce novel scientific results.

3.2.4.5.2 Canadian Science Capacity

Following the ACE-FTS mission, Canada has a network of research facilities with expertise in atmospheric remote sensing. Research groups are at U. of Waterloo, U. of Toronto, York U. and Dalhousie U. Industrial and governmental research and support has also come from the CSA, Environment and Climate Change Canada (ECCC), ABB-Bomem and Bristol Aerospace. These groups are also very interested in other Earth-observation techniques, and many host ground-based observatories, such as at the U. of Toronto, Saint Mary's U., Dalhousie U., and the dedicated research facility in Eureka, Nunavut: Polar Environment Atmospheric Research Laboratory (PEARL). These programs have supported a growing atmospheric science community and produced many HQP in atmospheric remote sensing. Canada also hosts a strong aerospace industry and several Canadian companies have contributed and been funded, to develop remote sensing mission proposals aimed at observing Mars, Earth and the Moon. These companies include ComDev, MPB Technologies, and MDA. Funding for these activities has come from NSERC, the CSA, and ECCC.

The ExoMars investigation was a partnership between the CSA, the Canadian community, and NASA's Jet Propulsion Laboratory (JPL). Following NASA's withdrawal from ExoMars, the loss of key people and technology at JPL made continuation unfeasible. Technologies under development at JPL included the new detector cryo-coolers, signal processing electronics, and telescope. For a future mission, Canadian science capacity would need to be increased to produce these technologies.

3.2.4.5.3 Enabling Canadian Technologies

ABB-Bomem is capable of producing vital components of the FTS instruments and has also provided interferometers for several space missions, such as ExoMars, GOSAT, and ACE-FTS. MPB-Technologies has been actively developing compact Fabry-Perot spectrometers intended for space application and has provided an instrument to GHGSat. MDA and ComDev are world leaders in spacecraft bus, electronics, and control infrastructure, and MDA was also an industrial partner for ExoMars. Bristol Aerospace provided the bus for SCISAT. The U. of Toronto and the CSA's David Florida Laboratory (DFL) both host clean rooms and vacuum chambers to evaluate spacecraft prior to launch. The Canadian community is capable of leading a mission of this type.

There is a growing commercial industry for Earth-Observation, and Canadian companies, such as UrTheCast, have been industry leaders. There is also a burgeoning industry for remote sensing beyond Earth orbit (asteroid mining, private missions to Mars). The technologies developed to enable a mission like ACE-FTS have already been demonstrated to have commercial value. For example, ABB-Bomem has been able to commercialize its interferometer technology and sell it for terrestrial applications, or to other governmental space industries.

3.2.5 PAT-03: Constrain the Dynamics of Planetary Atmospheres

Instruments to monitor atmospheric dynamics are needed to better understand landing environments (Mars), the large scale atmospheric circulation, the waves that drive it and the consequences for chemistry and constituent profiles (all planets), and internal composition of deep atmospheres (Gas Giants). Understanding atmospheres in our own solar system has implications for atmospheres in other solar systems. Wind measurements, apart from surface measurements on Mars are completely lacking and their lack is identified in the 2015 MEPAG Goals Document as being a major hindrance for the characterization of the state of the present climate of Mars' atmosphere. Instruments designed to measure winds on other planets are typically based on terrestrial designs and prototypes, but take advantage of phenomena or environments unique to other planets (e.g. using airglow to retrieve surface level and middle atmosphere winds on Mars, microwave radiometry to do deep sensing of the Jovian atmosphere). A large number of Canadian atmospheric researchers are involved with wind measurements and with modeling atmospheric dynamics. Canada leads research into terrestrial dynamical modeling and observation of terrestrial sites, is involved in the development of ESA's EDM-AEOLIS, and has past experience leading meteorological measurements on Mars. Canada has a strong potential to lead significant contributions, having in-house past experience with LiDAR, interferometry and meteorological sensors.

Dynamical results from exoplanetary systems and from gas giants make international news (winds on exoplanets, Saturn's polar Hexagon, weather reports from Mars, etc.). Winds and weather are accessible and understandable to the public broadly, across national boundaries. HQP involved with such a mission would gain skills that would benefit them in terrestrial applications of weather forecasting and observation. Atmospheric observations of other planets (particularly Mars and exoplanets) are expected to draw a large number of international researchers to Canada. HQP involved with this objective would gain skills working with large datasets that would be directly applicable both to current sectors like finance as well as the emerging field of "big data" analytics.

Instruments developed to examine the atmospheres of other planets may be spun off into earth-observing techniques for future commercial and governmental satellites. Numerical model improvements would be used to improve weather forecasting and climate change studies.

3.2.5.1 PAT-03-01: Preparatory Research: Development of a Canadian-led Dynamical Code with microphysics

(Rank #1 58.1/100)

Most of the motions of molecular atmospheres are invisible to optical observing techniques. This requires intensive numerical modeling to make determinations of the dynamics of planetary atmospheres. In Canada, there are models, particularly for Mars, which build on the Environment Canada GEM used for weather forecasting on Earth. Other researchers utilize planetary dynamical models derived from the popular Weather Research and Forecasting (WRF) model, developed by National Center for Atmospheric Research (NCAR). Implementations of WRF-derived dynamical models exist for Mars, Titan, Venus, Jupiter, Saturn and Pluto. On Earth, ensemble models (which average results from several different models) are particularly powerful tools. As such, the continued development of GEM for planetary applications alongside WRF is a valuable activity.

3.2.5.2 PAT-03-02: Preparatory Research: Determination of past wind directions from wind-derived surface features

(Rank #2 55.7/100)

Analysis of cloud tracking and meteorological data sets from existing spacecraft

(Rank #3 53.8/100)

To validate these models, it is critical to integrate existing data sets. This includes optical cloud tracking for the giant planets, temperature and aerosol retrievals on Mars, the morphology and rate of change of wind-derived surface features (e.g. sand dunes, yardangs, ventifacts). At the Martian surface, weather stations (such as Canada's MET and LiDAR on the Phoenix Lander or Rover Environmental Monitoring Station (REMS), MastCam and ChemCam on MSL) provide boundary conditions by providing temperature, pressure, downwelling and upwelling flux, water vapour column abundance, atmospheric opacity and direct measurements of wind speed and direction. The expression or absence of cloud provides evidence of super-saturation which can also constrain numerical models.

Instrument Development for Space: List of Potential Investigations

Dynamical instruments from orbit can be divided into two categories, both of which make use of the Doppler effect to measure windspeeds through interferometric techniques.

3.2.5.3 PAT-03-03: Instrument investigation: Develop LiDAR interferometric techniques for planetary atmospheres with aerosols with an accuracy of 5 m/s or better

(Rank #1 74.2/100)

The first technique is interferometry of scattered light from active narrow-band illumination, which uses a coherent laser for molecules and aerosols. ESA's EDM-AEOLUS is an example of this technique. Aerosols in particular, provide high return signals.

3.2.5.4 PAT-03-04: Instrument investigation: Develop airglow-based interferometric techniques for planetary atmospheres

(Rank #2 69.3/100)

These instruments make use of natural, but narrow emission lines from molecular species (such as airglow) to provide measurements of wind, temperature and volume emission rate. A terrestrial example of this technique is the Canadian Wind Imaging Interferometer (WINDII) instrument that flew on the Upper Atmosphere Research Satellite (UARS). The wind imaging technique has a long and strong Canadian heritage. The Canadian Dynamo Concept would extend this technique to Mars [8].

3.2.5.5 PAT-03-05: Instrument investigation: Develop advanced weather stations to measure windspeed, radiometric flux, optical depth and other parameters that directly affect dynamics

(Rank #3 67.5/100)

Located on landed vehicles, weather stations remain practical additions to space missions to provide boundary conditions. Canada has experience in these systems, through the Phoenix MET. Sensors could include a combination of pressure, temperature, relative humidity, bolometry (for fluxes), various wind sensors, Continuous Wave Lasers to illuminate near-surface aerosols, non-interferometric LiDARs, and/or all-sky cameras for cloud tracking.

3.2.5.6 PAT-03-06: Space System Development: Re-entry of small, low areal density spacecraft

(Rank #1 62.5/100)

Finally, as will be described in the secondary payloads section, there is an opportunity for Canada to contribute to small entry vehicles with very low areal density, precluding the need for ablative heat shields. Such technologies would be critical to the development of distributed networks that would be particularly helpful for dynamical and meteorological measurements.

3.2.5.7 PAT-03-07: Space System Development: High-Breakdown Threshold UV Optics

(Rank #2 60.9/100)

Active sensing systems may require significant power in order to generate the required signal to noise, accommodations for large-aperture optical telescopes and optical development in the ultraviolet region of the spectrum. These areas have been challenging for ESA’s Atmospheric Dynamics Mission (ADM)-Aeolus. Where Canada could most easily contribute is in the development of UV optics capable of withstanding high energy.

3.2.5.8 PAT-03-08: Space System Development: Automated processing of cloud tracking data

(Rank #3 60.9/100)

A second system development investigation is the automated reduction of meteorological data. In particular, atmospheric imaging acquires a great deal of data with the intention of retrieving a relatively small amount of information (e.g. dust/cloud opacity, wind direction). This suggests that developing means of processing this meteorological information onboard can reduce data volumes at the expense of computational resources (e.g. time) onboard the landed or orbital system.

3.2.5.9 PAT-03-09: Data analysis: Encourage the application of Terrestrial analogue datasets and techniques to problems in planetary atmospheres

(Rank #1 55.4/100)

Orbital imaging datasets exist for Mars and for several other atmospheres (e.g. Jupiter from Cassini and New Horizons, Titan and Saturn from Cassini) which allow for cloud tracking. There are also surface datasets from Mars and from Titan that lend themselves to continued analysis. This data is available publicly in repositories, such as the Planetary Data System (PDS) (pds.nasa.gov).

Additionally, there is a wealth of data from many comparable instruments for the Earth. This includes airglow interferometry (e.g. WINDII), orbital LiDAR (e.g. Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO)), cloud tracking and imagery (e.g. Geostationary Operational Environmental Satellite (GOES)), and weather station data provided by many national weather services, such as Environment Canada. By comparing new data to these, existing resources can enhance and deepen understanding of future results.

3.2.5.10 PAT-03-10: Secondary Payloads: Independently commandable weather stations/cloud tracking cameras for landed spacecraft and orbiters

(Rank #2 60.9/100)

Weather stations for landed missions provide excellent secondary payloads and are compact, with low power requirements. Simple sensors that could be used include pressure transducers, temperature sensors, relative humidity sensors, anemometers, bolometers (for upwelling / downwelling flux). The addition of small laser sources allows existing cameras to perform fog/near surface aerosol observation, which indirectly constrains atmospheric dynamics. Similarly, cloud-tracking cameras with large FOVs can be deployed on landed and orbital assets to passively observe the dynamics that moves these aerosol tracers. Benefits are realized, operationally, from separating such instruments from the primary payload with separated command pathways.

3.2.5.11 PAT-03-11: Secondary Payloads: Develop CubeSats capable of independent entry into planetary atmospheres

(Rank #1 71.6/100)

Such equipment could be a part of the primary payload, or be deployed as secondary payloads on separate small CubeSats/daughter spacecraft. For surface measurements, the larger the number of deployed stations, the better will be the dynamical validation. As such, a large number of very small entry vehicles (for instance at Mars) could be extremely valuable in developing a network of meteorological stations. Given their small mass, as compared to their surface area, such small stations could be deployed from orbit and would decelerate in the Martian atmosphere quickly without a need for ablative heat shields. Miniaturization now places missions, comparable to the US-proposed Pascal Mission, within the capabilities of Canada and would be a valuable contribution to Mars atmospheric science.

3.2.5.12 Summary for Objective PAT-03

3.2.5.12.1 Canadian Science Roadmap

Canadian participation on missions that will advance Objective PAT-03 will necessarily be opportunistic. As Mars is currently the site of the most concerted international exploration efforts, many of the investigations listed apply to this destination. Canadian interests, with respect to atmospheric exploration related to Objective PAT-03, are therefore effectively advanced through contributions to Martian space missions, both orbital (for global context) as well as landed (for boundary conditions). Canada’s experience with landed missions with meteorological stations, LiDARs and cameras is unmatched and can readily be deployed when opportunities occur. As such, the focus in the near term should be placed upon developing orbital atmospheric dynamics-measuring technologies and distributed secondary surface packages.

But Mars should not be our only target of interest. Canadian models and technologies can be a useful tool for investigating the dynamics of other atmospheres. Furthermore, beyond Mars it becomes possible to make more significant discoveries as less is known about these more distant and more exotic places. In the short term, Canada should focus on adapting the landed packages created for Mars (Cameras, LiDARs and Meteorological sensors) to locations of high interest, such as Titan, in order to be ready for exploration calls. We should also be prepared to look for savings in mass and power, which are much more limited commodities, the further we travel in the solar system. In the longer term, what is learned from orbital instruments at Mars can be applied further out.

3.2.5.12.2 Canadian Science Capacity

The number of planetary and space science groups studying atmospheric dynamics is relatively small with a few research groups of 10 researchers or less each located at UNB, York, U. of Toronto, Environment Canada, and the U. of Alberta. However, Canada has many researchers working in terrestrial atmospheric dynamics (>100), as evidenced by attendance at dynamics sessions at the Canadian Meteorological and Oceanographic Society meetings. Some portion of these researchers may be mobilized for a sufficiently interesting planetary mission (as was seen with the Phoenix Project), so there is considerable capacity.

Current facilities for the testing and preparation of instruments for flight are adequate (certainly, no less adequate than for other fields/objectives). Few experimental facilities exist which address dynamics specifically (e.g. no wind tunnels operating at low pressures or with exotic gas mixtures), though it is unclear whether such facilities are needed. The CSA program of high-altitude balloon launches is potentially quite useful, as conditions in the stratosphere resemble conditions at the Martian surface in both pressure and temperature. Lastly, the Environment Canada-maintained GEM model continues to improve. While GEM had been adapted to Mars in the past by J. McConnell, a new adaptation based on the more recent and improved version of the model could yield benefits for planetary atmospheric modeling and would provide a valuable counterpoint to US and European planetary atmospheric dynamics models.

3.2.5.12.3 Enabling Canadian Technologies

Canadian industry has significant experience with the manufacture of camera CCDs, LiDAR, lasers and meteorological sensors for space, with heritage from the MSL and Phoenix missions and with interferometers for examining airglow from the UARS mission. As such, Objective PAT-03 lends itself well to current capabilities. Benefits could be realized from extending our expertise from visible and near IR wavelengths into the UV and by developing lasers for space with both increased and decreased output power as compared to the Phoenix LiDAR laser to expand the range of potential mission contributions.

3.2.6 PAT-04: Understand Atmospheric and Exospheric Aerosols

Airborne dust/aerosols and exospheric dust are present in the Martian and lunar environments. In the case of Mars, airborne dust characterization may permit the detection of previously undetected mineral species because the optical and scattering properties of dust are fundamentally different from the same material present on the surface. Temporal monitoring of atmospheric dust would also provide insights into Mars atmospheric circulation and dynamics. Temporally and areally restricted changes in atmospheric dust load and composition may also serve as indicators of unique processes such as asteroid/comet impacts or volcanic eruptions. Such information could be used to target other orbital assets to regions of potential scientific interest.

In the case of the Moon, temporal variations in exospheric dust abundance and composition could also be indicative of impact or volcanic processes. Dust monitoring would serve as an “early warning” system that some sort of surface disruption process has occurred and the exospheric measurements would be used to narrow the search region that would be targeted for detailed follow-up investigations by other orbital assets.

Dust characterization on both Mars and the Moon would also contribute to future human exploration as dust has been identified as a potential human health hazard and can also negatively impact the performance of surface vehicles and equipment assets.

Measurement of dust optical properties via occultation or limb sounding is a well-established technique that has been applied to the Earth, Venus, and to a lesser extent, Mars. Evidence of exospheric dust on the Moon has been observed by Apollo astronauts and more directly quantified by the recent Lunar Atmosphere and Dust Environment Explorer (LADEE) mission.

Atmospheric/exospheric dust monitoring is an activity that sits at the interface between climatology and geology and is also highly relevant to human missions and engineering (performance of landed vehicles and equipment assets).

Canada is a leader in understanding astronaut health as well as atmospheric dynamics modeling and characterization of dust optical properties. This also builds on past experience in leading meteorological measurements on Mars (landed assets would provide complementary information to orbital data).

Canada has strong potential to lead significant contributions, given involvement in missions such as the Mars Phoenix lander, and the ExoMars TGO NOMAD occultation spectrometer.

The exploration of Mars is “hot” among the general public with new discoveries by rovers and orbiters making international headlines. Atmospheric dust is accessible and understandable to the general public and transcends national boundaries (e.g. volcanic eruptions in Iceland that have disrupted international air travel).

Because atmospheric/exospheric dust monitoring is interdisciplinary, and applicable to the Earth as well as other planetary bodies, it is expected to draw international talent. Also, because this area of research and exploration crosses diverse disciplines, it is expected that HQP involved in this work would be exposed to multiple disciplines and gain skills that would be applicable in multiple fields in industry and academia.

The techniques developed for dust monitoring would be readily transferable to terrestrial atmospheric monitoring. The importance of this is evidenced by international concern over air quality, particularly in large urban environments, as well as air quality associated with environmental degradation such as wildfires and desertification.

a) **Science questions:** An ability to characterize the spatial distribution, and physical and chemical properties of atmospheric dust enables us to address a number of important science questions, including atmospheric dynamics, both to trace atmospheric circulation and to validate global circulation models, and determining the composition of planetary atmospheres. In the latter case, atmospheric dust may provide an enhanced opportunity to detect the presence of minerals or compounds that are otherwise undetectable because they are obscured by other surface components. Related to this, dust/aerosols surrounding nominally atmosphereless bodies (e.g. Moon, Enceladus, Europa, Ceres, comets), here termed the exosphere, can provide more ready access to surface and subsurface materials of some bodies. From another perspective, atmospheric dust can complicate our ability to determine the surface composition of planetary surfaces, so improved dust characterization would improve planetary surface mapping.

b) **Current state of knowledge:** Tracing atmospheric dynamics using dust distribution has been demonstrated for Mars. It has been shown that planetary orbiters and flybys can successfully sample or detect exoatmospheric dust (e.g. Enceladus by Cassini, comet 67P/C-G by Rosetta, the Moon by LADEE, asteroid Ceres by Dawn). Direct detection of atmospheric dust is also possible from surface assets (e.g. Phoenix on Mars), and Earth-based telescopic observations.

c) **Rationale for Canadian priority:** Canada has strong expertise and heritage in atmospheric science, in both academia and government. Given this, the fact that atmospheric dust studies can address important high-order science questions related to areas such as habitability and origin of life and access to planetary interiors, and strong Canadian heritage (see below), continued Canadian activity in this area would benefit Canada's academic and space technology industrial sectors. Canada is also involved in the ExoMars TGO NOMAD instrument which will conduct solar occultation measurements of the Mars atmosphere.

d) **Past Canadian heritage:** Canada has a strong heritage in planetary atmospheric studies, most notably the MET on the Mars Phoenix lander, which included a sky-pointing LiDAR instrument to study atmospheric scatterers (dust/aerosols). Much expertise was also gained during the development of the MATMOS instrument for the ExoMars TGO which would have used solar occultation measurements to profile atmospheric gases and dust. The LiDAR technology was adapted by Canada into the OLA, which will be used to map the topography of asteroid Bennu.

e) **Possible mission opportunities:** The recent detection of dust/aerosols, presumably from the interior of Enceladus, that are indicative of habitability, has reinvigorated interest in icy satellite missions, and such missions are being actively explored and developed by ESA and NASA. Continued exploration of Mars and the Moon by numerous international space agencies also affords multiple opportunities for Canada to fly/refly solar occultation instruments (MATMOS heritage) and LiDARs (Phoenix MET heritage).

3.2.6.1 PAT-04-01: Preparatory Research: Laboratory investigations to understand dust-instrument interactions

(Rank #1 56.6/100)

Determining the composition of atmospheric/exospheric dust is possible using multiple direct analytical techniques, such as mass spectrometry, and atomic force microscopy. Preparatory research involves understanding how such technologies can be adapted for use on spacecraft, and how dust ingestion (often performed at high velocities) may affect data interpretation.

3.2.6.2 PAT-04-02: Preparatory Research: Laboratory investigations to understand optical properties of dust

(Rank #2 55.6/100)

As mentioned, Canada has strong heritage and ongoing involvement in the use of LiDAR and optical spectroscopy for dust/aerosol studies. Preparatory research to enable continued Canadian involvement includes investigating the applicability of multi-wavelength LiDAR for dust compositional characterization, and how hyperspectral solar occultation spectroscopy can be better used to determine key dust properties, such as grain size distribution, grain shape, and composition, through a combination of laboratory studies and optical modeling. Laboratory studies would benefit from long-pathlength environment chambers that would better simulate occultation measurements that would be made by spacecraft.

3.2.6.3 PAT-04-03: Instrument investigation: Mass spectroscopy, atomic force microscopy optical spectroscopy

(Rank #1 63.6/100)

While the development of spacecraft instruments for direct characterization of dust is not currently a significant Canadian strength, Canada does possess relevant strengths in analytical chemistry that could be enhanced and exploited for this purpose. In terms of optical characterization of dust, Canada has world-class expertise in LiDAR, which could be extended to enable multi-wavelength LiDAR systems which would allow for improved dust characterization.

In terms of optical characterization of dust, Canada has significant strengths: the Phoenix MET station, the (now-cancelled) MATMOS instrument on the ExoMars TGO, and participation in the ExoMars TGO NOMAD instrument.

Measurement needs depend on the specific body being investigated. However, in general, an ability to characterize the temporal and spatial distribution of dust, and its physical and chemical properties, are desirable. Direct detection is geared toward the latter two, while optical characterization is geared toward all of them.

Although somewhat outside the scope of this Objective, lasers are integral to LIBS and Raman spectroscopy, so Canada is well placed to contribute to these areas.

3.2.6.4 PAT-04-05: Instrument investigation: Develop specialized instrumentation to measure particle size distribution of aerosols from the surface of Mars and Titan

(Rank #2 52.1/100)

Such instruments could be laser or LED-based nephlometers or may use other techniques in a small payload to achieve this measurement.

3.2.6.5 PAT-04-06: Instrument Investigation: Develop all-sky scanning and multi-wavelength LiDARs

(Rank #1 71.9/100)

Because optical characterization of dust is a Canadian strength, we focus on this aspect of system development. The dust Objective can involve surface or orbital assets. For surface assets, dust characterization using LiDAR would benefit from an all-sky scanning ability. Multiple wavelength laser capability, which has not yet been performed beyond the Earth, would allow better dust characterization. Surface observations of atmospheric dust would also benefit from an ability to measure direct solar illumination (Sun-staring instrument that track the Sun and with multi-wavelength capability). Solar occultation measurements have been demonstrated by other international groups on a number of planetary missions. Thus, the technical challenges are understood and have been overcome. Occultation measurements can be performed by orbiting spacecraft maneuvering or a gimbaled instrument.

Such instruments could also be considered as primary instruments on a secondary payload. Because of previous and current Canadian experience, requirements are reasonably well understood. For atmospheric dust observations, an all-sky scanning LiDAR is desirable (and can build on OLA MATMOS and Phoenix MET experience). For solar occultation measurements, vertical profiling is desirable and could be accomplished by a gimbal mount or spacecraft slewing.

3.2.6.6 PAT-04-07: Data Analysis: Work on analysis of data from current spectrometers/ LiDARs for information extraction

(Rank #1 58.3/100)

To advance this Objective, analysis of data from existing solar occultation instruments, such as Spectroscopy for Investigation of Characteristics of the Atmosphere of Mars (SPICAM) and the Planetary Fourier Spectrometer on ExoMars, and Spectroscopy for Investigation of Characteristics of the Atmosphere of Venus (SPICAV) / Solar Occultation at Infrared (SOIR) on Venus Express, would be very beneficial. In the near term, detailed analysis of data from the ExoMars TGO NOMAD instrument will provide valuable operational experience as well as working with actual Mars data.

While analogue sites would be of some limited utility to this investigation, more beneficial are laboratory facilities that can be used to investigate multi-wavelength LiDAR and solar occultation measurements under well-controlled conditions. Such facilities are present in Canada but need to be advanced.

3.2.6.7 PAT-04-08: Astronaut-led Investigation: Develop dust characterization and sampling techniques for astronaut health protection

(Rank #1 53.6/100)

It is unlikely that astronaut-led investigations are necessary or will realistically be undertaken, except in the long-term. Direct characterization of exospheric dust is doable by automated instruments. However, astronauts would be well placed for both sample collection and characterization in a controlled facility, as automated instruments have operational limitations. For atmospheric dust studies, we are interested in both spatial and temporal properties, which are probably best addressed by automated surface instruments. As with exospheric dust, direct analysis of dust is probably better accomplished in a controlled environment by a human researcher.

3.2.6.8 Summary for Objective PAT-04

3.2.6.8.1 Canadian Science Roadmap

Characterizing the physical and compositional properties of dust differs from the approach for characterizing temporal and spatial variations. For physical-chemical characterization, enhanced laboratory facilities to characterize dust are required. Specifically, this requires appropriate dust/aerosol chambers that can be interfaced to optical spectrometers in occultation geometries and LiDAR systems. Investigation of the enhanced science return possible with multi-wavelength LiDARs should be undertaken. These investigations should be accompanied by optical modeling refinements to determine the uniqueness of future observations and for instrument/observation definition and optimization.

For temporal-spatial characterization, further developments of all-sky scanning LiDARs should be undertaken. Additionally, sun-tracking optical technologies should be pursued. Support of data analysis from existing solar occultation planetary instruments should be undertaken.

Canada should look to capitalize on its extensive heritage in spectroscopy and LiDAR for future flight opportunities. Dust characterization is important to the scientific investigation of multiple bodies, both atmosphere-bearing and nominally airless. Consequently, Canada should actively pursue the numerous near- and medium-term international flight opportunities that exist to other planetary bodies in the context of dust characterization.

3.2.6.8.2 Canadian Science Capacity

Canada possesses strengths in planetary environment chambers, atmospheric modeling, and LiDAR - all technologies that are relevant to this Objective. Key facilities and expertise exist at a number of institutions and space technology companies (U. of Winnipeg, U. of Toronto, Dalhousie U., Optech, MDA, Neptec, INO, ABB) with new facilities coming on-line (e.g. York U.).

New capacity is required in terms of laboratory facilities that enable fine-grained dusts to be produced and aerated and coupled with appropriate instrumentation (LiDARs, optical spectrometers). Recent facilities have been established with funding from the CFI. CSA and NSERC are the main funders of expertise in these areas.

3.2.6.8.3 Enabling Canadian Technologies

Pertinent engineering capabilities and strengths reside in both academia (e.g. York U., U. of Winnipeg) and industry (e.g. MDA, Optech, ABB, Neptec). These organizations are well placed to advance the necessary technology and laboratory facilities. New capacity needs include dust chambers with appropriate capabilities to reproduce long path lengths and interface with suitable LiDARs and spectrometers.

There are a number of potential benefits to Canada:

(1) optical spectroscopy and LiDAR are existing Canadian strengths;

(2) dust characterization is scientifically important for studying a number of planetary bodies;

(3) numerous potential flight opportunities for dust characterization instruments exist and will emerge, involving multiple international agencies and missions; and

(4) the developed techniques can be applied to terrestrial atmospheric and climate change studies.

3.2.7 References

- *3.2.2 PAT-01: Understand Mars Surface-Atmosphere Interactions*

  [1] *Smith et al. Science 2009*
  [2] *Whiteway et al. Science 2009*
  [3] *Hecht et al. Science 2009*
  [4] *Glavin et al. J. Geophys. Res. 2013*
  [5] *Nikolakakos and Whiteway Geophys. Res. Lett. 2015*
  [6] *Gough et al. Planet Sci. Lett. 2011*
  [7] *Chojncki et al. J. Geophys Res. 2016*
  [8] *Ojha et al. Nature Geoscience 2015*
  [9] *Davila et al. Astrobiology 2010*
  [10] *Whiteway et al. J. Geophys Res. 2008*
  [11] *Daerden et al. Geophys. Res. Lett. 2010 2015*

- *3.2.3 PAT-02: Understand the Chemistry of Planetary Atmospheres*
  - *3.2.3.1 Preparatory Research*

  [1] *Olsen K. S. G. C. Toon C. D. Boone and K. Strong. New temperature and pressure retrieval algorithm for high-resolution infrared solar occultation spectrometry: analysis and validation against ACE-FTS and COSMIC. Atmos. Meas. Tech.* ***9*** *1063-1082 (2016) doi:10.5194/amt-9-1063-2016.*
  [2] *Wennberg P. O. V. J. Hipkin J. R. Drummond G. C. Toon M. Allen J.-F. Blavier L. R. Brown A. Kleinbohl J. P. D. Abbatt B. Sherwood Lollar K. Strong K. A. Walker P. F. Bernath R. T. Clancy E. A. Cloutis D. J. Desmarais J. M. Eiler Y. L. Yung T. Encrenaz and J. C. McConnell. MATMOS: the Mars atmospheric Trace Molecule Occultation Spectrometer in Mars Atmosphere: Modelling and observation (2011) edited by F. Forget and E. Millour 480-481.*
  [3] *Vandaele A.C. E. Neefs R. Drummond I. R. Thomas F. Daerden J.-J. Lopez-Moreno J. Rodriguez M. R. Patel G. Bellucci M/ Allen F. Altieri D. Bolsée T. Clancy S. Delanoye C. Depiesse E. Cloutis A. Fedorova V. Formisano B. Funke D. Fussen D. A. Geminale J.-C. Gérard M. Giuranna N. Ignatiev J. Kaminski O. Karatekin F. Lefèvre M. López-Puertas M. López-Valverde A. Mahieux J. McConnell M. Mumma L/ Neary E. Renotte B. Ristic S. Robert M. Smith S. Trokhimovsky J. VanderAuwera G. Villanueva J. Whiteway V. Wilquet and M. Wolff and the NOMAD Team. Science objectives and performances of NOMAD a spectrometer suite for the ExoMars TGO mission. Planet. Space Sci. 119 233–249 (2015) doi:10.1016/j.pss.2016.03.003.*
  [4] *Olsen K. S. G. C. Toon and K. Strong. Simulation of source intensity variations from atmospheric dust for solar occultation Fourier transform infrared spectroscopy at Mars. J. Mol. Spectrosc. 323 78–85 (2016) doi:10.1016/j.jms.2015.11.008.*
  [5] *Daerden F. L. Neary J. Whiteway C. Dickinson L. Komguem J. C. McConnell J. W. Kaminski. Simulating the Phoenix Lander meteorological conditions with a Mars GCM in European Geosciences Union General Assembly 14 (2012) edited by A. Abbasi and N. Giesen 12628.*
  [6] *Rhind T. J. Ronholm B. Berg P. Mann D. Applin J. Stromberg R. Sharma L.G. Whyte and E.A. Cloutis. Gypsum-hosted endolithic communities of the Lake St. Martin impact structure Manitoba Canada: Spectroscopic detectability and implications for Mars. International Journal of Astrobiology 13 366-377 (2014) doi:10.1017/S1473550414000378.*
  [7] *Godin P. J. A. Cabaj S. Conway A. C. Hong K. Le Bris S. A. Mabury and K. Strong. Temperature-dependent absorption cross-sections of perfluorotributylamine. J. of Mol. Spectrosc. 323 53-58 (2016) doi:10.1016/j.jms.2015.11.004.*
  [8] *Nasser R. and P. Bernath. Hot methane spectra for astrophysical applications. J. Quant. Spectrosc. Radiat. Transf. 82 279-292 (2003) doi:10.1016/S0022-4073(03)00158-4.*

- *Instrument Development for Space*

  [1] *Bernath P. F. C. T. McElroy M. C. Abrams C. D. Boone M. Butler C. Camy-Peyret M. Carleer C. Clerbaux P.-F. Coheur R. Colin P. DeCola M. DeMaziere J. R. Drummond D. Dufour W. F. J. Evans H. Fast D. Fussen K. Gilbert D. E. Jennings E. J. Llewellyn R. P. Lowe E. Mahieu J. C. McConnell M. McHugh S. D. McLeod R. Michaud C. Midwinter R. Nassar F. Nichitiu C. Nowlan C. P. Rinsland Y. J. Rochon N. Rowlands K. Semeniuk P. Simon R. Skelton J. J. Sloan M.-A. Soucy K. Strong P. Tremblay D. Turnbull K. A. Walker I. Walkty D. A. Wardle V. Wehrle R. Zander and J. Zou. Atmospheric Chemistry Experiment (ACE): Mission overview Geophys. Res. Lett. 32 L15S01 (2005) doi:10.1029/2005GL022386.*
  [2] *Wennberg P. O. V. J. Hipkin J. R. Drummond G. C. Toon M. Allen J.-F. Blavier L. R. Brown A. Kleinbohl J. P. D. Abbatt B. Sherwood Lollar K. Strong K. A. Walker P. F. Bernath R. T. Clancy E. A. Cloutis D. J. Desmarais J. M. Eiler Y. L. Yung T. Encrenaz and J. C. McConnell. MATMOS: the Mars atmospheric Trace Molecule Occultation Spectrometer in Mars Atmosphere: Modelling and observation (2011) edited by F. Forget and E. Millour 480-481.*
  [3] *Moreau L. F. Grandmont S. Lantagne R.Desbiens M.-A. Soucy. An interferometer for compact imaging spectrometer. Proc. SPIE 6661 666109 (2007) doi:10.1117/12.736911.*
  [4] *Dejian F. K. A. Walker K. Sung C. D. Boone M.-A. Soucy and P. F. Bernath. The portable atmospheric research interferometric spectrometer for the infrared PARIS-IR. J. Quant. Spectrosc. Radiat. Transf. 103 362–370 (2006) doi:10.1016/j.jqsrt.2006.05.006.*
  [5] *Kuze A. H. Suto M. Nakajima and T. Hamazaki. Thermal and near infrared sensor for carbon observation Fourier-transform spectrometer on the Greenhouse Gases Observing Satellite for greenhouse gases monitoring. Appl. Opt. 48 6716 (2009) doi:10.1364/AO.48.006716.*
  [6] *C. T. McElroy C. R. Nowlan J. R. Drummond P. F. Bernath D. V. Barton D. G. Dufour C. Midwinter R. B. Hall A. Ogyu A. Ullberg D. I. Wardle J. Kar J. Zou F. Nichitiu C. D. Boone K. A. Walker and N. Rowlands. The ACE-MAESTRO instrument on SCISAT: description performance and preliminary results. Appl. Opt. 46 4341-4356 (2007) doi: 10.1364/AO.46.004341.*

- *Instrument Investigations*
  - [1] *Wennberg P. O. V. J. Hipkin J. R. Drummond G. C. Toon M. Allen J.-F. Blavier L. R. Brown A. Kleinbohl J. P. D. Abbatt B. Sherwood Lollar K. Strong K. A. Walker P. F. Bernath R. T. Clancy E. A. Cloutis D. J. Desmarais J. M. Eiler Y. L. Yung T. Encrenaz and J. C. McConnell. MATMOS: the Mars atmospheric Trace Molecule Occultation Spectrometer in Mars Atmosphere: Modelling and observation (2011) edited by F. Forget and E. Millour 480-481.*
  - [2] *Korablev O. F. Montmessin A. Trokhimovskiy A.A. Fedorova A.V. Shakun A.V. Grigoriev B.E. Moshkin N.I. Ignatiev F. Forget F. Lefèvre K. Anufreychik T.O. Kozlova N. Semena Y.S. Ivanov A. Kungurov Y.K. Kalinnikov A.Y. Titov A.V. Stepanov A. Zharkov A. Semenov D. Patsaev F. Martynovich A. Sidorov A. Viktorov D. Timonin O. Sazonov V. Shashkin A. Santos-Skripko I. Maslov I. Dzuban I. Stupin D. Merzlyakov V. Makarov Y. Nikolskiy F. Altieri G. Arnold D.A. Belyaev D.S. Betsis J.L. Bertaux N. Duxbury T. Encrenaz J.C. Gerard S. Guerlet D. Grassi T. Fouchet P. Hartogh Y. Kasaba I. Khatuntsev V.A. Krasnopolsky R.O. Kuzmin E. Lellouch M.A. Lopez-Valverde M. Luginin A. Määtänen E. Marcq J. Martin Torres A. Medvedev E. Millour V.I. Shematovich K. S. Olsen M. Patel C. Quantin-Nataf A.V. Rodin I. Thomas N. Thomas L. Vazquez M. Vincendon V. Wilquet C. Wilson L.V. Zasova L.M. Zelenyi M.P. Zorzano. The Atmospheric Chemistry Suite (ACS) of three spectrometers for the ExoMars 2016 Trace Gas Orbiter. Space Sci. Rev. in press (2017).*
  - [3] *Neary L. F. Daerden J. W. Kaminski and J. C. McConnell. Modelling Mars Chemistry and Meteorology with the GEM-Mars GCM in European Geosciences Union General Assembly 12 (2010) edited by A. Abbasi and N. Giesen 10472.*
  - [4] *Etiope G. and B. Sherwood Lollar. Abiotic methane on Earth Rev. Geophys. 51 276–299 (2013) doi:10.1002/rog.20011.*
  - [5] *Olsen K. S. G. C. Toon C. D. Boone and K. Strong. New temperature and pressure retrieval algorithm for high-resolution infrared solar occultation spectrometry: analysis and validation against ACE-FTS and COSMIC. Atmos. Meas. Tech. 9 1063-1082 (2016) doi:10.5194/amt-9-1063-2016.*
  - [6] *Olsen K. S. G. C. Toon and K. Strong. Simulation of source intensity variations from atmospheric dust for solar occultation Fourier transform infrared spectroscopy at Mars. J. Mol. Spectrosc. 323 78–85 (2016) doi:10.1016/j.jms.2015.11.008.*

- *3.2.4 Secondary Payloads*
  - [1] *Wennberg P. O. V. J. Hipkin J. R. Drummond G. C. Toon M. Allen J.-F. Blavier L. R. Brown A. Kleinbohl J. P. D. Abbatt B. Sherwood Lollar K. Strong K. A. Walker P. F. Bernath R. T. Clancy E. A. Cloutis D. J. Desmarais J. M. Eiler Y. L. Yung T. Encrenaz and J. C. McConnell. MATMOS: the Mars atmospheric Trace Molecule Occultation Spectrometer in Mars Atmosphere: Modelling and observation (2011) edited by F. Forget and E. Millour 480-481.*
  - *3.2.4.4 PAT-02-19: Astronaut-led Investigation: Man-portable FTS for Earth-Observation*
  - [1] *McElroy C. T. J. B. Kerr D. I. Wardle L. J. B. McArthur G. M. Shah M. Garneau S. G. MacLean R. Thirsk J. A. Davies W. F. J. Evans R. W. Nicholls J. C. McConnell and M. Cann. SPEAM-I (sunphotometer Earth atmosphere measurement) observations of high-altitude ozone from STS 41-G. Can. J. Phys. 69 1123-1127 (1991) doi :10.1139/p91-171.*
  - [2] *McElroy C. T. J.B. Kerr L. J. B. McArthur D. I. Wardle and D. Tarasick. SPEAM-II Experiment for the Measurement of NO2 O3 and Aerosols in Ozone in the Troposphere and Stratosphere in Proc. Quad. Ozone Symp. 1992. (1994) NASA Conf. Publ. 3266 891*

- *3.2.5 PAT-03: Constrain the Dynamics of Planetary Atmospheres*
  - [1] *Whiteway et al. (2009) Mars water ice clouds and precipitation. Science.*
  - [2] *Moores et al. (2010) Atmospheric Dynamics at the Phoenix Landing Site as seen by the Surface Stereo Imager JGR*
  - [3] *Dickinson et al. (2010) GRL*
  - [4] *Moores et al. (2015) Observational evidence of a suppressed planetary boundary layer in northern Gale Crater Mars as seen by the Navcam instrument onboard the Mars Science Laboratory rover. Icarus*
  - [5] *Moores et al. (2016) Advances in Space Research*
  - [6] *Moore et al. (2016) A full martian year of line-of-sight extinction within Gale Crater Mars as acquired by the MSL Navcam through sol 900. Icarus*
  - [7] *Kloos et al. (2016) The first Martian year of cloud activity from Mars Science Laboratory (sol 0-800). Advances in Space Research*
  - [8] *Ward et al. 2002*

- *Instrument Development for Space: List of Potential Investigations*
  - [1] *W.E. Ward W.A. Gault N. Rowlands S. Wang G.G. Shepherd I.C. McDade J.C. McConnell D. Michelangeli and J. Caldwell An imaging interferometer for satellite observations of wind and temperature on Mars the Dynamics Atmosphere Mars Observer (DynAMO) In Proceedings of SPIE Vol 4833 "Applications of Photonics Technology V" edts. R.A. Lessard G.A. Lampropoulos G.W. Schinn 226-236 2002.*
  - [2] *Smith C.L. Cooper B.A. and Moores J.E. (2016) Possible ground Fog from SLI imagery of Titan. Icarus.*
  - [3] *Taylor P.A. et al (2008) Temperature Pressure and Wind Instrumentation in the Phoenix Meteorological Package. J. Geophys. Res.: Planets*
  - [4] *Moores et al. (2011) Observations of near-surface fog at the Phoenix Mars landing site. Geophys. Res. Lett.*
  - [5] *Moores et al. (2011) Motivation for Atmospheric Measurements of Water Ice using the Mars Science Laboratory Instrument Suite and beyond. European Planetary Science Conference.*
  - [6] *Haberle R.M. and the Pascal team (2003) Third International Conference on Mars Polar Science and Exploration October 13-17 2003 Alberta Canada abstract no.8075*

3.3 Planetary Geology, Geophysics and Prospecting

Community Report from the Planetary Exploration Topical Team on Planetary Geology Geophysics and Prospecting

Table 3-3 Planetary Exploration - Planetary Geology Geophysics and Prospecting Topical Team

(Student and postdoc names are shown in italics)

Name	Affiliation
Gordon **Osinski** (Chair)	University of Western Ontario
Haley Sapers (Exec Sec)	University of Western Ontario
Neil Banerjee	University of Western Ontario
Audrey Bouvier	University of Western Ontario
Kieran Carroll	Gedex Inc.
Ed Cloutis	University of Winnipeg
Michael Daly	York University
Roberta Flemming	University of Western Ontario
Paul Fulford	MDA
Nadeem Ghafoor	Canadensys Aerospace
Rebecca R. Ghent	University of Toronto
Christopher Herd	University of Alberta
Mark Jellinek	University of British Columbia
Catherine Johnson	University of British Columbia
Richard Léveillé	McGill University
Phil McCausland	University of Western Ontario
Penny Morrill	Memorial University of Newfoundland
Catherine Neish	The University of Western Ontario
Stephane Ruel	Neptec Design Group
Claire Samson	Carleton University
Mariek Schmidt	Brock University
Ian D'Souza	COM DEV
Sean Shieh	University of Western Ontario
Sabine Stanley	University of Toronto
Kim Tait	Royal Ontario Museum
Livio Tornabene	University of Western Ontario
Peter Visscher	Ontario Drive and Gear, Ltd.
Anthony Withers	University of Western Ontario
Lyle Whyte	McGill University
Mike Zanettli	University of Western Ontario
Elise Harrington	University of Western Ontario
Patrick Hill	University of Western Ontario
Erin Bethell	Carleton University

3.3.1 Introduction to Planetary Geology Geophysics and Prospecting in Canada

Canada encompasses one of the most diverse geological records on the planet. It possesses a wide range of rock types including some of the most ancient rocks in the world (formed over 4 billion years ago), active volcanoes and vast polar regions dominated by permafrost and shaped by glacial and periglacial processes. Canada's geology has played a fundamental role in shaping the Canadian identity, from providing inspiration and raw materials for artists to affecting distribution of population centres, to being a major driver in the growth and present-day strength of our economy. Indeed above all else, Canada is recognized as a world leader in mining and mineral exploration. Estimated mineral production in 2014 (the last year that reliable numbers are currently available) was $44 billion providing jobs to 375,000 Canadians. This pillar of the economy is underpinned by mineral prospecting and exploration. Prospecting entails the search for economically valuable deposits of minerals and is typically thought of as the first stage of the geological analysis of a region prior to the second stage of exploration, which focuses on establishing the nature of a known mineral deposit prior to development.

Canadian geoscientists are recognized worldwide for expertise and innovation in field-based geological mapping and prospecting, geophysical surveying and modeling, and laboratory-based studies of rocks and minerals. The same methods successfully applied to investigating Earth are being adapted by Canadian geoscientists in the planetary sciences. This synergy, combined with our long history of mining and access to a wealth of terrestrial analogue sites, puts Canadian geoscientists in a unique position to undertake new geological geophysical and prospecting investigations of the terrestrial planets, rocky and icy moons, and asteroids throughout the solar system.

Over the last decade, Canada has also played an important role in the MSL mission through the contribution of APXS. The instrument was developed and built in collaboration of CSA, the industrial prime contractor MDA Space Missions (Brampton, ON) and the science team led by the U. of Guelph. The project strengthened the collaboration of Canada with NASA and in particular JPL, a key institution for future planetary missions. It solidified the capabilities of Canadian industry and scientists by the seamless integration of the Canadian instrument into the overall mission objectives, which address many of the objectives in this chapter. Since landing in 2012, the APXS has contributed significantly to the overall scientific return of MSL, assembled an experienced team for the daily operations, and enabled many Canadian scientists the opportunity to participate in this mission.

Through consultation with the Canadian community we have defined 6 objectives for Planetary Geology Geophysics and Prospecting: The clear priority for the community in terms of overall scientific merit and impact is:

- PGGP-01 Document the geological record and processes that have shaped the surface of the terrestrial planets, their moons, icy satellites and asteroids;

The next two priorities both ranked equally highly in terms of scientific merit and impact; however Objective PGGP-02 (resources) was ranked the highest out of all objectives for the potential for innovations that could contribute to Canada's economic growth, and in terms of the novelty of the science that can be conducted.

- PGGP-02 Determine the Resource Potential of the Moon Mars and Asteroids;
- PGGP-03 Understand the origin and distribution of volatiles on the terrestrial planets and their moons asteroids and comets;

The final 3 objectives in priority order are:

- PGGP-04 Determine the interior structure and properties of the terrestrial planets and their moons, icy satellites and asteroids;
- PGGP-05 Understand the impact, threat and hazards posed by impact events on the Earth and other solar system bodies;
- PGGP-06 Understand surface modification processes on airless bodies.

Investigations are presented for each of these objectives. These investigations primarily revolve around preparatory research, instrument development and data analysis. Many of the proposed instruments are applicable to multiple objectives and multiple planetary bodies as described below.

We have identified 2 cross-cutting Investigations that are common to and would support all 6 objectives:

(1) A Canadian analogue research program (Preparatory Research Investigation) and

(2) A data analysis program for the investigation of planetary mission data and samples (Data Analysis Investigation).

3.3.2 PGGP-01: Document the geological record and processes that have shaped the surface of the terrestrial planets, their moons, icy satellites and asteroids

(1) Objective and Rationale

The surfaces of planetary objects are a witness-plate to the evolution of the solar system over the past 4.5 billion years. The geological record of rocky and icy objects informs us about the processes that have shaped or continue to shape their surfaces. A substantial proportion of all space missions have had a geologic focus documenting the morphology, morphometry and composition of surface materials. We now have superb high-resolution (cm-scale) imaging data for the Moon and Mars. Mercury, Venus, certain asteroids and the icy satellites of Jupiter and Saturn have lower resolution data available. The ongoing New Horizons and Dawn missions have provided the first resolved images (and other data) of the surface of the asteroid Vesta and the dwarf planets Ceres and Pluto. Regolith breccia present in meteorite collections provide laboratories with hand samples of extraterrestrial surface environments. Understanding the geological record and surface processes of these worlds is intertwined with our understanding of planetary interiors (PGGP-04) and provides a critical framework for determining the resource potential of the Moon, Mars and asteroids (PGGP-02). Understanding the surface modification processes on airless bodies is called out in a separate objective (PGGP-06) as is the origin and distribution of volatiles on the terrestrial planets and their moons, asteroids and comets (PGGP-03). Understanding the end result (i.e. impact craters) of the impact of asteroids and comets with planetary objects is an important aspect of this objective; whereas understanding the impact threat and hazards posed by impact events is outlined separately in PGGP-05.

(2) Current State of Knowledge and Knowledge Gaps

Planetary exploration missions and ground-based telescopic observations have shown that impact cratering is the one geological process common to all objects in the solar system with a solid surface. In addition to providing valuable information to help us better understand the impact, cratering process impact craters act like drilling probes into planetary interiors (PGGP-04) by way of their excavation of ejecta, and in complex craters, the uplift of rocks to form more accessible central peaks and rings [5]. On the Moon, minerals and rock types not present in the Apollo returned sample or lunar meteorite collections have been detected in impact craters resulting in new (unanswered) questions about the make-up of the lunar crust and its origin and subsequent evolution (e.g. [6]). Impact crater morphology also provides important insights into the properties of crustal rocks (e.g. craters on Ceres have been shown to be shallower than predicted suggesting some relaxation of the crust is occurring at the present day [7]). Finally craters provide the only way to estimate the age of planetary surfaces (through cratering counting) in the absence of samples returned from known locations for which we only currently have data from the Moon. The source and make-up of impactor populations is also poorly understood and has changed through time (e.g. [2]). Despite its importance to planetary geology, there remain many outstanding questions about the impact cratering process and its effect on the origin and evolution of planetary bodies and on life itself.

In addition to the exogenic process of impact cratering, various solar system objects have been or continue to be affected by endogenic geological processes. The most common endogenic process is volcanism which has affected all the terrestrial planets, the Moon, and many moons and asteroids [8]. There are evolving but still controversial results suggesting that that Venus [9] and Mars [10] may still be volcanically active and even on the Moon, volcanism may have occurred as recently as a few tens of millions of years ago. In the outer solar system, evidence for cryovolcanism is mounting (e.g. [8]) and the Jovian moon Io is considered the most volcanically active object in the solar system yet to be discovered.

Mars remains a major focus of the Canadian and international planetary science communities. In addition to impact cratering and volcanism, it has been proposed that its surface has also been affected by fluvial, lacustrine, aeolian and hydrothermal processes – all processes that involve the action and involvement of liquid H_2O [12]. This raises important questions about the potential for life on Mars, making it an important destination for the Canadian astrobiology community (see Chapter 3.1 – Astrobiology). The geological record of Mars also preserves important information about the evolution of its climate over the past 4 billion years, providing in turn important clues to its atmosphere through time (see Chapter 3.2 - Planetary Atmospheres).

In addition to the Martian polar caps, of high importance to the Canadian community is evidence for putative, glacial and periglacial landforms and deposits over vast regions of the Martian surface – landforms that are ubiquitous in the Canadian Arctic (e.g. [13]). Indeed it is now thought that Mars has gone through one or more ice ages in the relatively recent geological past [14]. This offers exciting opportunities for comparative planetology through terrestrial analogue activities. When combined with the exciting discovery of ice deposits near the poles of Mercury and the Moon and the volatile-rich nature of many small bodies, this has resulted in a separate objective (PGGP-03) on the origin and distribution of volatiles on the terrestrial planets and their moons, asteroids and comets.

There is also a large diversity of worlds present in the outer system from planet-sized satellites to small comets at the edge of the solar system. These icy worlds teach us about the evolution of the outer solar system and how planet formation proceeds in cooler environments than those experienced in the inner solar system. Some of the larger satellites are also known to possess subsurface oceans of liquid water – so-called “Ocean Worlds”. These objects are of great interest to outer solar system science due to their potential to host life. The discovery of a second genesis of life in an Ocean World is perhaps the most exciting science question in outer solar system science. Outer solar system science thus aims to (1) identify ocean worlds in the solar system and (2) evaluate their habitability.

(3) Possible Mission Opportunities

There are several near- and medium- term mission opportunities to address this objective. NASA’s Next Mars Orbiter (NeMO) scheduled for launch in 2024 is the nearest-term prospect for Canadian instrument contributions, representing an exciting opportunity for the Canadian planetary geoscience community. As defined in the MEPAG NEX-SAG, a polarimetric radar instrument to characterize ice within a few meters of the surface is considered a critical contribution to this mission. Canada has substantial expertise in this area on both the science and the engineering sides. Beyond NeMO, the Canadian planetary geology and geophysics community sees participation in Mars Sample Return as a high priority, and the CSA is encouraged to seek ways for Canada to contribute to the fetch rover mission and in pre-mission analogue sample studies, as well as in subsequent sample analysis.

The Moon is seeing a resurgence of interest and there are several missions confirmed and being planned for the next decade. For Canada, there are various opportunities to contribute to international missions and increasingly, the potential for purchase space on commercial landers and orbiters. China is arguably the most active player in terms of frequency of missions within its lunar exploration program, but there are also several new players including India, Japan, Israel and Korea, each of whom have orbiters and/or landers planned over the next few years, many of which represent both co-investigator and hosted payload opportunities for Canada. ESA is collaborating with Russia on their Luna-25 -26 and -27 missions and participation from Canada is encouraged.

There are also two other new types of opportunity for Canada to contribute to lunar exploration. First, because of its relatively close proximity, micro-satellite missions to the Moon are deemed feasible. NASA has announced the first round of micro/nano orbiters to be flown within five years, leveraging rideshare opportunities aboard the new generation of US (government and commercial) launch vehicles. Canadian-led micro-satellite missions to the Moon are considered feasible and within the scope of the CSA budget. The second emerging opportunity is for science enabled by humans at a deep space habitat [15] including lunar surface science using telerobotics and human assisted lunar sample return.

In terms of outer solar system exploration, a mission to Europa was a top priority of both the 2003 and 2013 Planetary Science Decadal Surveys undertaken by the NRC of the National Academies. The recent discovery of plumes of icy material jetting from the interior of Enceladus and Europa has strengthened interest in outer solar system science. As a result, NASA has recently been authorized to start development of a multiple-flyby mission of Europa with the possible addition of a Europa lander. ESA is also planning a mission to Jupiter in the same time frame to explore its icy moons before going into orbit about Ganymede. Longer term prospects for outer solar system exploration are also encouraging. NASA's New Frontiers 4 call allows mission proposals to Enceladus and Titan and NASA is developing an Ocean Worlds program that could lead to multiple missions to the outer solar system in the next few decades launched with the Space Launch System (SLS) rocket.

The NASA New Frontiers and Discovery competitions offer exciting opportunities for Canadian involvement in future missions. The priority New Frontiers opportunities are: Venus in Situ Explorer, Lunar South Pole-Aitken Basin Sample Return Mission, Lunar Geophysical Network, Trojan Tour and Rendezvous, Cometary Nucleus Sample Return, and Ocean Worlds (Titan and Enceladus).

3.3.2.1 PGGP-01-01: Preparatory Research: Re-initiation of a Canadian Analogue Research Program

3.3.2.1.1 Description of the Investigation

The Canadian planetary science community has collectively called for the CSA to reinstate CARN or Field Investigation Grant programs on several occasions and we do so again here. With the renewed emphasis on capacity building at the CSA we feel that there is an even more important role for an updated CARN or Field Investigation Grants program. Analogue studies also enable critical preparatory activities to be carried out that feeds forward into future mission opportunities. This investigation is to reinstate a grants program to fund analogue field activities. The program should be annual applications, should be kept concise and the amounts should be $30 to 50K per year for 2 years. It is noted that such an analogue program is a high priority for the Astrobiology TT. A separate and/or additional program aimed at supporting high fidelity end-to-end analogue missions is also viewed as area that Canadians can provide leadership internationally.

3.3.2.1.2 Science Objectives

Terrestrial analogues are places on Earth that approximate in some respect the geological environmental and/or putative biological conditions on a particular planetary body, either at the present-day or sometime in the past [1]. Such studies enable comparative planetology investigations to be conducted which are critical for ground truthing observations made by spacecraft on other planetary bodies. Analogue studies have been deemed a high priority by the Canadian and international planetary science communities. Investigation of terrestrial analogues provides an ideal opportunity to foster collaboration between Canadian and international solid earth science, planetary science and biological science communities. Analogue sites also enable the testing and development of hardware and operations concepts in realistic environments.

3.3.2.1.3 Published Canadians

Enabled by the original CARN program, Canadians were leaders in terrestrial analogue research. A decade-old review of analogue sites and analogue research is provided in [1]. There is a substantial body of research published by Canadians on terrestrial analogues. Researchers from the following universities were supported by the CARN program: U. of Alberta (Herd), U. of British Columbia (Laval, Suttle), McGill U. (Nadeau, Pollard, Whyte, Wing), McMaster U. (Slater), Memorial U, of Newfoundland (Morrill ,Sylvester), U. of Toronto (Barfoot), U. of Western Ontario (Banerjee, King, Osinski), and U. of Winnipeg (Cloutis). Over a hundred HQP were provided valuable hands-on training.

3.3.2.1.4 Canadian Research Facilities

As noted above, a review of analogue sites and analogue research is provided in [1]. In brief Canada is blessed with a range of world-class analogue sites. Impact and volcanic processes dominate the geology of solar system objects other than the Earth. There are 30 meteorite impact craters in Canada including several well-preserved and exposed structures in northern terrains. Volcanic terrains and rocks ranging from years to billions of years old are present from coast to coast. The Canadian Arctic offers a plethora of analogue sites including vast regions of continuous permafrost subjected to glacial and periglacial processes, the world's highest latitude perennial springs, ice-covered lakes and unique biological habitats. Canada also boasts the oldest rocks on Earth and, courtesy of mining, access to the deep subsurface - both can be considered important analogue sites for the study of the origin and evolution of life. There are other numerous sites across Canada.

3.3.2.2 PGGP-01-02: Preparatory Research: Development of a program to further the understanding of the effect of curation and preparation methods on the intrinsic properties of returned samples from the Moon Mars and asteroids

3.3.2.2.1 Description of the Investigation

Develop a grants program to fund activities and facilities that specifically address sample curation and preparation research, which is defined as research aimed at understanding the degree to which returned samples can be contaminated or compromised in the course of curation including – but not limited to – field collection, transport, initial investigation, documentation, subdivision sample preparation (e.g. cutting, polishing, thin section production), analysis, cataloguing and storage. Research could involve analogue materials (thereby complementing Preparatory Research #1) or astromaterials in the form of meteorites.

3.3.2.2.2 Science Objectives

This research program would address the specific objective of understanding the effect of curation and handling on the intrinsic properties of the samples, and inform the development of specific curation and handling protocols for astromaterials specific to the parent body target from which they were collected. Curation Research would include an end-to-end approach allowing for the study of all aspects of the sample return process, from analogue sample studies and collection planning to actual sample collection on the parent body initial non-destructive investigation upon sample return, storage and subsequent targeted analysis on Earth.

Although other agencies do research on best methods for curation that is specific to their facilities, an end-to-end approach would be a unique perspective to be offered by Canada; this program would advance knowledge in this area specifically for sample return missions. This will enable the CSA to play a significant role in NASA's OSIRIS REx in which Canada is already partnered and slated to receive asteroid samples, as well as in Japanese, Chinese or European sample return and space exploration programs that are open to collaborative analysis. It is in the interest of the CSA to have trained researchers and facilities that will be fully prepared to participate in sample return missions from international missions, from beginning (planning) to end (sample analysis). Preparation for these sample return and curation activities is also an important contributor in future human exploration, where major objectives will include the efficient careful collection and handling of samples.

3.3.2.2.3 Published Canadians

Canadians are leaders in the specific area of cold curation and non-destructive sample analysis. The Subzero Facility for Curation of Astromaterials at the U. of Alberta funded by NSERC and the Government of Alberta is the first (and so far only one) of its kind consisting of a purified argon atmosphere glove box enclosed within a -10 to -30 °C freezer. The facility which was developed nominally for curation of pristine samples of the Tagish Lake meteorite is of significant interest in the astromaterials community and is applicable to curation of almost any pristine astromaterials sample. Commissioning of the facility has demonstrated the advantages of cold curation for the mitigation of terrestrial contamination; the design of the facility and its commissioning are described in [1]. The Royal Ontario Museum (ROM) is a leader in curation of astromaterials and other terrestrial samples. Recently a multi-million dollar upgrade to the Earth Sciences collection spaces has added the capacity for more hands-on teaching and group facilities for discussions, as well as a state-of-the-art low humidity storage facility for the astromaterials. An ultra-low temperature freezer (-85°C) houses the Tagish Lake meteorite at the ROM. Expertise in the curation and non-destructive analysis of meteorites exists at universities and Government facilities across Canada, including the U. of Alberta, U. of Calgary, ROM, Western U., and the Canadian Museum of Nature. It is envisioned that existing facilities could be used to develop the optimal end-to-end methods for future sample return, including incorporating analogue sample return deployments. Such a program would help lead to the development of other curation research facilities through infrastructure grants.

3.3.2.2.4 Canadian Research Facilities

The analytical facilities in place at Western are engaged to develop analytical methods adapted to the sample-size and composition requirements, but there is a need for new laboratory spaces dedicated to space-returned materials, to avoid terrestrial contamination and preserve their pristine compositions. Such facilities currently do not exist in Canada, while they have been set up in USA and Japan for samples returned from space missions (e.g. Apollo, Startdust, Genesis, Hayabusa). For example, the Geometric Laboratory at Western combines multiple analytical methods (microscopy, microanalysis, chemistry, mass spectrometry) for trace metal geochemical studies of geological and planetary materials. These techniques require extremely low levels of contamination that cannot be achieved without facilities dedicated to *only* extra-terrestrial material preparation. To elevate Canada internationally in the field of planetary material analysis, cleanroom facilities for development of end-to-end handling of space materials need to be established. Such expertise and facilities will place together Canada at the forefront of research in cosmochemistry and advance fundamental knowledge about the origin of our own planet Earth and planetary systems in general.

3.3.2.3 PGGP-01-03: Instrument Investigation: Development of radar and its deployment on missions to map planetary surfaces

3.3.2.3.1 Measurement Needs for Instrument

Canada has significant experience in radar development through the RADARSAT program, with a focus on short-wavelength synthetic aperture radars. This experience could be leveraged to map other planetary surfaces. In addition to the Earth, synthetic aperture radars have flown on orbital missions to Venus (NASA’s Magellan mission) the Moon (ISRO’s Chandrayaan-1 and NASA’s Lunar Reconnaissance Orbiter) and Saturn (NASA’s Cassini mission). However many worlds remain to be explored at these wavelengths (primarily Mercury, Mars, and several icy satellites). High-resolution multi-wavelength polarimetric radar investigations would yield important additional information for the worlds already studied. Needed technology development in this area includes (1) the development of sensors that operate at different wavelengths (longer wavelengths are needed to study buried ice deposits (P-band), while shorter wavelengths are needed for surface characterization), and (2) the development of polarimetric radar systems that utilize less power and are less massive than their terrestrial counterparts. Previous studies ([1]; [2]) are consistent with the outcomes of the Final Report of the MEPAG NEX-SAG, which concluded that a “Polarimetric radar imaging (SAR) with penetration depth of a few (<10) meters” was critical for addressing the resource science and reconnaissance objectives of the NeMO mission.

3.3.2.3.2 Science Objectives

Radar data is critical for constraining the roughness of a planetary surface. This is critical not only for follow-up landed investigations but also for the geological mapping and interpretation of planetary surfaces. Surface roughness data provides a unique complementary dataset to visible and multispectral imagery. Radar is also extremely useful for identifying large near-surface reservoirs of water ice which, in addition to being an interesting science question on many planetary bodies, is needed for in situ resource utilization for human exploration. For Mars, which represents the highest priority target for a Canadian planetary radar, determining the overall spatial and vertical distribution of shallow ground ice deposits in the Martian mid- to high-latitudes is a high priority. Further science objectives for a Mars radar instrument include: mapping and quantifying shallow ground ice in areas of possible brine flow, and monitoring for recent RSLs and gullies, both of which are hypothesized to form through the involvement of liquid water; determining the surface properties of impact and volcanic deposits; and mapping fluvial landforms in ancient Martian terrains.

3.3.2.3.3 Building on Instrument / Previous Studies

Canada has a long heritage of designing, building and operating radar instruments as exemplified by the Radarsat series of Earth Observation missions. To date, there has been no instrument development or prototyping for planetary radars. There have however, been several previous concept studies for a Mars Synthetic Aperture Radar (SAR); the most recent was awarded to MDA on March 20 2017 for the potential contribution of this instrument to the proposed NASA NeMO. Radar missions to other planetary bodies – in particular Venus – are considered important by the Canadian planetary geology and geophysics community.

3.3.2.4 PGGP-01-04: Instrument Investigation: Development of LiDAR systems for the surface and orbital characterization of planetary surfaces

3.3.2.4.1 Measurement Needs for Instrument

Surface elevation data is arguably one of the most important datasets for exploring planetary bodies from both orbit and *in situ*. Elevation data is key for defining a geospatial framework (i.e. a planetary datum) to which all datasets are tied or referenced, to maximize comparative studies of datasets in a Geographical Information System (GIS). Surface morphometry (e.g. slope, roughness, topography, etc.) derived from elevation is vital and must be constrained to an appropriate scale to be useful for assessing the safety and traversability for robotic and human landing sites on planetary bodies. Canadian LiDAR expertise primarily resides in scanning systems using either time of flight or triangulation laser ranging. Scanning systems have the ability to collect data anywhere in their FOV and can thus dynamically select the scan area and data density. This is well suited for planetary mapping applications where relative motion is relatively slow and sparse data over a wide FOV is desirable. This approach also provides the ability to collect high resolution 3D images in support of science objectives. Furthermore, scanning LiDAR sensors can achieve very high dynamic range, penetrate atmospheric dust and are lighting immune. The ability to scan independent of spacecraft motion is also useful because it allows the instrument to map larger areas of the planetary surface, and in the case of comets and asteroids, it allows enough coverage to get the full shape model.

3.3.2.4.2 Science Objectives

A LiDAR system addresses Objective PGGP-01 by yielding information on the high-resolution shape of surface features. This in turn allows investigators insight into geologic processes. High resolution LiDAR allows for the analysis of regolith distribution, surface roughness, ground patterns (e.g. polygonal terrain in the northern regions of Mars) boulder distribution, linear topographic features, etc. All of these give significant information about the geologic history of the surface. LiDAR yields the shape of large scale features such as volcanoes, channels, deltas, etc. LiDAR yields the overall shape model of asteroids and comets which gives tremendous information about their formation and modification history. It is noted that both rover-mounted and orbital LiDAR systems are considered under this investigation.

It is also noted that only the Moon possesses topographic information of sufficient resolution to meet future robotic and human exploration needs. While the Mars Orbiter Laser Altimeter (MOLA) on the 2001 Mars Global Surveyor provided us with the first nearly global coverage elevation data of Mars, the data was collected at a spatial scale that requires improvement to be of further use as a geospatial referencing system for much higher resolution datasets, and for landing site safety and traversability characterization. The current global interpolated gridded Digital Terrain Model (DTM) from MOLA has a spatial resolution of ~468 m/pixel, which is built by individual foot prints that are on the order of ~168-m in diameter and with an along-track and cross-track spacing of ~300 m and 4 kilometers respectively, and a vertical precision of ~1 m [1]. As a comparison, the Lunar Orbiter Laser Altimeter (LOLA) developed almost a decade later has a 5-point (5-meter spot size/20-m FOV) foot print with a minimum spacing of ~25 m and spacing of ~50 m between shots [2]. Implementing a comparable spatial improvement similar to the LOLA or OLA instruments at Mars would provide significant improvements to Martian topographic datasets for a variety of purposes.

3.3.2.4.3 Building on Instrument / Previous Studies

Canada has strong capability and heritage in scanning LiDAR technology for space that could be used to support planetary surface mapping. For example, Canadian scanning LiDAR technology was used on the following missions: Phoenix Mars Lander; Space Shuttle Laser Camera System (LCS); Space Shuttle TriDAR rendezvous and docking sensor; Cygnus TriDAR rendezvous and docking sensor; OLA. Through the Space Technology Development Program (STDP) and ExCore prototyping projects, the CSA has funded the development of LiDARs capable of supporting planetary rover missions (e.g. Integrated Vision System (IVS), Integrated Vision, Imaging and Geological Mapping Sensor (IVIGMS), LIDAR Navigation and Imaging Sensor (LINIS), etc.). This led to the development of hardware capable of supporting analogue missions. While LiDARs have very desirable characteristics for planetary missions, development is still required to further reduce their overall footprint (mass volume power), especially in the context of smaller platforms. For planetary surface investigations, the development LiDAR of LiDAR integrated with other image data, in particular visible and multispectral, is considered a high priority with potential terrestrial applications.

3.3.2.5 PGGP-01-05: Instrument Investigation: In situ mineral XRD for characterization of mineralogy and mineral resources on planetary surfaces

3.3.2.5.1 Measurement Needs for Instrument

Most rover-based instruments measure chemical information from minerals. It is desirable to deploy an XRD instrument to obtain complimentary crystal structural information from minerals. The Chemistry and Mineralogy (CheMin) instrument currently deployed on the Curiosity Rover on Mars is such an instrument; however CheMin requires preparation of a pulverized sample to be placed inside the body of the rover. We advocate the development of an *in situ* X-ray Diffraction instrument (ISXRD) situated on a robotic arm which will directly analyze minerals *in situ* on coarse- or fine-grained rock or sediment surfaces, yielding mineralogical information in context in the field without requiring sample collection and pulverization. A key feature of this method is its ability to non-destructively identify sample mineralogy, with no sample preparation an obvious advantage for spacecraft-borne observations where sample pulverization for conventional XRD analysis is problematic. ISXRD would provide *in situ* mineralogical information complementary to the *in situ* chemical data currently provided by APXS on Curiosity and Planetary Instrument for X-Ray Lithochemistry (PIXL) on Mars2020. In addition to mineral identification, ISXRD will yield quantitative textural information regarding grain size [1] and strain-related mosaicity of minerals ([2];[3]). Moreover high-pressure polymorphs will be discernable by ISXRD enhancing recognition of impact-related rocks.

3.3.2.5.2 Science Objectives

ISXRD would perform mineralogical analysis of intact rock specimens *in situ,* to provide mineral identification with crystal structural parameters using well-established technology as seen on lab based instrumentation [4]. However this instrument would be miniaturized and require lower power. Requirements include a microfocused source (e.g. [5]) and detector (e.g. CCD or Hybrid Pixel Array Detector (HPAD)) and low energy input (CheMin draws 19 Watts). While this instrument has been envisaged for some time [6], the resources to build a prototype have not been available.

3.3.2.5.3 Building on Instrument / Previous Studies

A miniaturized ISXRD unit would enable exploration on Canada's frontiers and could be mounted as a payload for missions to the Moon, Mars, or asteroids to enhance exploration of these planetary bodies. While this instrument has been envisaged for some time [6], no appropriate opportunities have been available. An internally-funded concept study has been conducted at Western U.

3.3.2.6 PGGP-01-06: Instrument Investigation: Raman spectrometer for planetary exploration

3.3.2.6.1 Measurement Needs for Instrument

The instrument should measure mineralogy and organics. Gating capability to measure time-dependent laser-induced fluorescence is also useful as it allows an independent assessment of organics present in the target. Remote Raman spectrometers allow the mission team to characterize areas that are not in reach of hardware on a lander or rover. Arm-mounted Raman spectrometers allow sensitive characterization of areas closer to a rover or lander that can be immediately sampled for delivery to other instruments on the spacecraft, or for caching for future delivery to laboratories on Earth. Raman spectrometers can also be used to investigate samples that have already been acquired. Raman spectrometers can be combined with a LIBS instrument to yield elemental abundance as well as an assessment of mineralogy and organics.

3.3.2.6.2 Science Objectives

Raman spectrometers address cross-cutting science questions that pertain to geology prospecting atmospheric studies and astrobiology investigations. Further Raman is relatively non-destructive compared to other techniques and can be conducted from a distance. A Raman spectrometer addresses Objective PGGP-01 by yielding information on the mineralogy and organics contained within a target rock ice soil or regolith sample. Information about minerals and organics is indicative of previous environments and geological processes. For example, specific minerals such as hematite indicate aqueous processes. Raman spectrometers will be useful for many targets including Mars, the Moon, other moons in the solar system and asteroids. Raman can also be used to address objectives PGGP-02, PGGP-03, PGGP-05 and PGGP-06. In particular, Raman systems with mapping (rastering) capabilities yield a detailed survey of a given target sample. Fluorescence measurements can be integrated into a Raman system and improve the discrimination between organics.

3.3.2.6.3 Building on Instrument / Previous Studies

Raman spectroscopy has been the subject of previous concept studies and prototyping programs. Universities throughout Canada have expertise in Raman investigations that is necessary for the analysis of data from a Canadian instrument. For example, several researchers at York U. have published on the utility of UV Raman including its use in identifying organics present in geologic materials, and in looking at exchange of water between the atmosphere and Mars simulants (e.g. [1]). Another application is looking at weathering and mineral phase distribution in meteorites (e.g. [2]). A number of researchers at ROM and the U. of Western Ontario are also using Raman in their research, including looking into the ability of Raman systems to give insight into shocked materials. Canada has invested in a Science Definition Study and in Space Technology Development Projects for Raman instruments.

3.3.2.7 PGGP-01-07: Instrument Investigation: 3D microscope for planetary exploration

3.3.2.7.1 Measurement Needs for Instrument

A microscopic imager should be versatile and have the ability to collect low- and high-resolution imagery, both true and false colour images in both 2D and 3D. The ability to acquire UV and multispectral datasets is important for many science objectives including those related to astrobiology.

3.3.2.7.2 Science Objectives

One of the fundamental techniques when exploring planetary surfaces regardless of the focus (i.e. whether it is geologically versus astrobiologically focused) is the ability to capture a visual record of the target of interest at various scales – from regional (km-scale) to outcrop (m- to cm-scale) to microscopic (mm- to µm-scale). This provides important context at multiple scales for other supporting data sets. A microscopic imager represents one of the most basic tools required for geology and astrobiology, and it is anticipated that most if not all future surface missions to Mars and the Moon will carry one. A microscopic imager essentially mimics a field geologist's hand lens in the field and a microscope in the laboratory setting. In order to properly classify rock types and the soils derived from them, it is essential to obtain information on the chemical and physical attributes of these materials (e.g. grain size shape alignment/sorting etc.).

3.3.2.7.3 Building on Instrument / Previous Studies

In late 2009 CSA began development of Three-Dimensional Multispectral Microscopic Imager (TEMMI) in association with two industrial partners: MDA and INO along with a science team led by Western U. A prototype of this instrument exists. TEMMI is an optical instrument that provides high-resolution colour images to investigate microstructures and microtextures of soils and rock surfaces, and is intended to compliment other rover instruments providing data at coarser resolution scales. The device was designed as one of several instruments to be mounted on a robotic arm which has also been developed in recent years by CSA and its partners. It has been used in laboratory setting [1] and in analogue field trials [2] but requires further science maturation work in order to increase its TRL ready for a suitable flight opportunity.

3.3.2.8 PGGP-01-08: Instrument Investigation: Improved APXS for Mars Moon and Asteroids

3.3.2.8.1 Measurement Needs for Instrument

The APXS [1]) is arguably the most mature instrument for in situ chemical composition on planetary surfaces. With heritage on Pathfinder 2, MER rovers, Rosetta and MSL, it currently provides the most comprehensive collection of chemical data available from the Martian surface. It was used to establish the average crustal composition of Mars [2], and significantly constrained and enhanced the interpretation of all mineralogy results from the surface with Moessbauer or IR spectroscopy and XRD. It is invaluable for geological reconnaissance during traverse and for sample triage. The capability to reliably quantify the chemistry, including key elements like S, Cl, Br and P, added significantly to our current understanding about the environmental conditions of early Mars. The availability of APXS data from all rover landing sites allows integrated investigations tying together the landing sites, as well as provides ground truth for orbital data and Martian meteorites.

3.3.2.8.2 Science Objectives

In situ chemistry is one of the fundamental tools of planetary exploration and addresses PGGP-01-04. As an essential investigation for sample triage and geologic context, it enables and complements other investigations. It is suitable for Mars asteroids and the Moon.

3.3.2.8.3 Building on Instrument / Previous Studies

The APXS represents a mature design with the latest implementation on MSL developed in Canada. Two MER and the MSL instruments operated successfully all together for 25 years under Martian condition indicating that key components (x-ray detector sources required electronics components) and the design are extremely reliable. The experience of long term operations on several missions with different constraints has led to recent design improvements. Beside increased sensitivity through multiple and increased detector area, a key advance would be the addition of a 3D movement stage that allows for rastering samples independently of the rover arm deployment and Central Processing Unit (CPU). A rover would deploy the APXS overnight and the sensor head would autonomously move across an area larger than the single FOV and collect a series of shorter spectra. On board data analysis could guide the placement and optimize the statistics needed for adequate results on each spot. This would greatly enhance the scientific return and simplify rover operations

Besides the instrumentation, Canada is also a leader in the analysis of the APXS data. The U. of Guelph houses the APXS calibration facility as well as a Particle-Induced X-ray Emission (PIXE) accelerator, which shares much of the APXS method principles and which is used for terrestrial analogue research.

3.3.2.9 PGGP-01-09: Instrument Investigation: Integrated Vision System for planetary exploration

3.3.2.9.1 Measurement Needs for Instrument

An IVS would combine three sub-systems: a LiDAR instrument which would generate a spatial point cloud, a visible camera to capture Red Green Blue (RGB) images, and a spectrometer to collect mineralogical and compositional data.

3.3.2.9.2 Science Objectives

As noted above (see PGGP-01-07 description) the ability to capture a visual record of the target of interest at various scales – from regional (km-scale) to outcrop (m- to cm-scale) to microscopic (mm- to µm-scale) is one of the fundamental required techniques when exploring planetary surfaces. The characterization of an outcrop is a key first step and is typically done by means of mast-mounted cameras. Current and upcoming rovers typically take the traditional approach of visible imagery more recently with limited multispectral capabilities (e.g. PanCam on the ExoMars 2020 rover). The use of stereo cameras further permits 3D images to be created. Following the lead of recent vision systems used on the Martian rovers, an IVS could be used as both a navigation system for a rover as well as a scientific instrument for studying Mars.

3.3.2.9.3 Building on Instrument / Previous Studies

A prototype IVS instrument was developed in late 2009 by Optech and MDA under the CSA prototyping program. A prototype of this instrument exists but it requires further science maturation work in order to increase its TRL ready for a suitable flight opportunity. The development of an IVS system would build on several other studies that have investigated the use of LiDAR for planetary exploration, both as a navigation aid and as a science instrument.

3.3.2.10 PGGP-01-10: Data Analysis: A data analysis program for the investigation of planetary mission data and samples

3.3.2.10.1 Description of the Investigation

This investigation is to develop a grant program to fund analysis of spacecraft mission data. This could be modelled on the CARN program with annual competitions and amounts of $30 to 50K per year for 2 years. Activities related to this program should not just be restricted to the analysis of data *sensu stricto,* but should also enable analysis of extraterrestrial samples and modelling and laboratory studies critical to enable the better interpretation and analysis of mission data.

3.3.2.10.2 Science Objectives

The study of planetary surfaces cannot be done without the analysis of mission data. There is no current program to fund the analysis of mission data, unlike in the US, and it is a difficult thing to get funding from NSERC to do so. The study of planetary samples such as meteorites and samples returned from past, current, and future space missions, is critical to understand the origin history, and the physical conditions of formation of planets in the Solar System. Such information is first of all fundamental to human kind, but can also be used to plan future planetary exploration program (mission sites, mining exploration) and also understand the formation of exoplanets in other nearby star systems. There is no current CSA program to fund the analysis of planetary samples unlike in the US with NASA, and it is also difficult to receive funding from NSERC CFI or other Canadian or provincial agencies for such fundamental and leading science.

3.3.2.10.3 Published Canadians

A large percentage of the Canadian planetary geology, geophysics and prospecting community conduct analysis of mission data and/or the analysis of planetary materials.

3.3.2.11 Summary for Objective PGGP-01

3.3.2.11.1 Canadian Science Roadmap

A series of investigations has been proposed that, if implemented, would result in a radical increase in research conducted by Canadian scientists. Priorities are the following low-cost grants programs: Canadian Analogue Research Program; a program to further the understanding of the effect of curation and preparation methods on the intrinsic properties of returned samples from the Moon, Mars, and asteroids; and a data analysis program for analysis of planetary mission data and samples. This must be combined with regular opportunities to propose and develop new science instruments. This will enable this community to participate in international missions throughout the Solar System.

3.3.2.11.2 Canadian Science Capacity

There is significant strength related to this objective in Canada. At Western, several members of the Centre for Planetary Science and Exploration (CPSX) conduct research related to understanding the geological record and processes that have shaped the surface and interiors of the terrestrial planets, their moons, icy satellites and asteroids. There is a core group of researchers (Bouvier, Brown, Flemming, McCausland, Moser, Neish, Osinski, Stooke, Tornabene, Wang, Wiegert, Withers), who study planetary surface processes throughout the solar system with strengths in analogue studies, remote sensing, and the analysis of astromaterials to understand the differentiation (from core to crust) and impact histories of planets and planetesimals. At the U. of Alberta, there is a wide range of expertise in remote sensing and sample analysis. This includes the largest University-based meteorite collection in Canada, including samples of a variety of asteroid types, the Moon, and Mars. Main groups: Herd (sample analysis and meteorite curation), Rivard (remote sensing); part of campus-wide virtual institute (Institute for Space Science Exploration and Technology).

The U. of Winnipeg (Cloutis) is involved in analysis of data from a number of Mars missions (orbiters and rovers) as well as upcoming missions (ExoMars rover Mars 2020). This work is complemented by laboratory experiments involving environment chambers that simulate various planetary surfaces (e.g. Moon, Mars, asteroids) in order to elucidate how a planetary body's surface environment affects our ability to determine its composition. At McGill U., faculty members in Earth and Planetary Sciences Geography and Natural Resource Sciences have expertise in planetary surface composition and processes (especially on Mars), in geochemical instrumentation (e.g. LIBS-Raman, XRF/XRD/APXS) and experience with the MSL ExoMars and Mars 2020 missions. The MSI is a growing campus-wide initiative.

At Memorial U. in the Department of Earth Sciences, Drs. Leitch and Morrill are investigating the use of geophysical measurements (e.g. Self-Potential (SP), Electromagnetic Induction (EMI) and magnetics) to elucidate geochemical magnetic and structural features associated with subsurface serpentinization at a Mars analogue site. At the U of New Brunswick, there are strengths in impact cratering and Mars geology (Spray). At Carleton, there is considerable expertise in Venus geology (Samson) and at Brock U., Fueten and Schmidt focus on Mars surface processes.

3.3.2.11.3 Enabling Canadian Technologies

Canadian industry has been developing planetary rover and robotics technologies since 2008 under multiple CSA Exploration Core (ExCore) and STDP contracts and grants/contributions. This work has resulted in in the development of key Enabling Technologies, ranging from proof-of-concept models (TRL 1-2) to hardware and systems that have been tested under relevant environmental conditions (TRL 6). Such elements include rover system architecture, drivetrain wheels, navigation sensors and software thermal management systems, low temperature sensors and electronics deep-space capable micro-mission technologies, manipulators, and drilling / coring technologies. These technologies will enable Canadian-led or Canadian participation in surface exploration missions to terrestrial planets and their moons within the next decade, particularly the Moon and Mars, to address scientific objectives in areas of research, including geological record and processes, interior structure and properties, resource potential surface modification processes, and origin and distribution of volatiles (e.g. water ice).

Such missions will not only provide valuable science return but will also be opportunities for Canadian technologies to obtain flight heritage, thus progressing them to the highest TRL (9), and giving Canadian industry a competitive edge for these technologies on the world stage. In terms of surface imaging capabilities, a range of different capabilities exist across Canadian industry (e.g. MDA, Neptec, Honeywell, Canadensys, MPB and ABB). A number of Canadian organizations have also developed enabling technologies for micro/nano orbiter and/or surface mission elements that present affordable options for Canada to make near term progress in addressing this objective.

3.3.3 PGGP-02: Determine the Resource Potential of the Moon Mars and Asteroids

(1) Objective and Rationale

Asteroid mining was first envisioned in Garrett Serviss' 1889 *Edison's Conquest of Mars*. In recent years, the concept of exploiting extraterrestrial solar system material has since transcended the realm of fiction into what is now a serious field of study, as exemplified by the recent start-up of several high-profile space resource companies such as Deep Space Industries Inc. and Planetary Resources Inc. Given the human race's ever-growing appetite for raw materials, the virtually limitless amount of resources available in space and the possibility of moving mining and processing off-Earth and away from our fragile ecosphere, the stage is set for exponential expansion of space resource exploration and development activities in the coming decades and centuries. This has the potential to quickly out-strip the nearly-flat budgets which the world's national space agencies can make available for space exploration. For this reason, a few countries, such as Luxemburg, are positioning themselves strategically to take advantage of this new 21st century economic opportunity.

As noted in the introduction to this chapter, Canada is recognized as a world leader in mining. One foundation for this strength is our expertise in mineral prospecting and exploration, and another is the suitability of Canada's taxation regulatory and financial systems to encourage development of mining as a profitable commercial business; the juncture of these two is the reason why Toronto has become the centre of the world's mineral resource exploration community, holding their largest annual meeting for many years. Prospecting represents the first stage of the geological study of a region and is focused on the search for economically valuable deposits of a particular resource. Unlike most other developed countries on Earth, much of our vast Canadian landmass remains underexplored. As such, Canadian companies and universities are at the forefront of developing new approaches and technologies for mineral prospecting and exploration. With combined expertise in rovers, drilling and instrumentation, Canada is well placed to lead the international solar system resource exploration efforts.

(2) Current State of Knowledge and Knowledge Gaps

The immediate future of asteroid mining is likely to focus on the extraction of water and other volatile compounds for use in in-space applications; the economics of delivering refined resources to Earth from space will likely postpone terrestrial markets for space resources for quite some time. Water can be used to sustain astronauts, grow plants, etc. The oxygen can also be used for astronauts to breathe. Water can also be separated into its constituent H and O components via electrolysis to be used as rocket propellants [1], and water and other volatiles can also be used directly as propellants for warm-gas thrusters. Numerous questions remain about the amount of H_2O and other volatiles locked up in the various asteroid types and the ease of extraction. Most of the information we have about individual asteroids comes from Earth-based telescopic spectra, and only a handful of asteroids have been studied *in situ*. While meteorites can also provide information on asteroid compositions, linking individual meteorites to individual asteroids is difficult to do with certainty; also their passage through the atmosphere selectively destroys more of the weaker water-rich bodies before they reach the ground, making it more difficult to extrapolate from the properties of recovered meteorites to assess asteroidal resource potential. Thus, a necessary next step, and one being proposed by various asteroid mining companies, is the development of small prospecting spacecraft to visit and assess a large number of asteroids.

Medium-term in-space markets for other types of resources may also develop. For example, structural metals (iron, nickel etc.) may find use in developing eventual large structures in space with Solar Power Satellites seen as a potential large-scale market, and a crewed Cis-Lunar Habitat/Fuel Depot as a potential nearer-term market. “Dirt” from asteroids could even find customers in a manner similar to aggregate quarrying, providing radiation shielding to protect crew in, for example a Cis-Lunar Habitat station, from occasional solar flares. In the long-term, various metals may eventually be mined. One group of often-touted resources is the Platinum Group Elements (PGEs,) a group of 7 elements with atomic numbers 44 – 46 and 76 – 78. They are extremely valuable by weight in terrestrial markets, even more so than gold, due to their relative scarcity in Earth's crust and their use in catalytic converters and in jewelry. Many classes of meteorites are known to be enriched in PGEs, some as much as several times the richest deposits on Earth; however, very few studies have been conducted regarding the types of PGE-bearing minerals, how they might be extracted, etc. Asteroid-sourced PGEs may eventually be able to be delivered economically to Earth’s surface; in the meantime they may find use in in-space industrial applications.

As with asteroids, mining the Moon for natural resources has long been studied. Asteroid mining may be a more attractive initial target for resource exploitation due to the small gravity field of most asteroids, making it easier to reach their surface and to launch mined material from their surface. Lunar resource exploration and mining on the other hand, will require development of Lunar landers sized large enough to land the exploration mining and processing equipment; for off-Moon markets, it will also require Lunar surface launch vehicles capable of transporting the resulting products to their destination market (e.g. a Cis-Lunar Habitat/Fuel Depot). As this will also eventually involve development of substantial infrastructure on the Lunar surface, resources produced in situ on the Moon may also usefully be used to help develop that infrastructure and stock it with certain consumables, rather than transporting them from Earth. Extensive studies have been conducted on this topic, most recently during NASA’s Constellation Program - circa 10 years ago. The potential for finding and exploiting water ice from permanently shadowed regions at the Lunar poles is of particular interest in terms of providing consumables for use by crew and propellant for Lunar launch vehicles, as well as for sale to spacecraft owners in cis-Lunar space. Structural materials (metals regolith for shielding) from the Moon can also radically reduce the total cost of building up large-scale infrastructure on the Moon.

As for Mars, all modern plans for crewed missions to Mars' surface count on making use of local resources (In Situ Resource Utilization (ISRU)) in order to minimize the amount of such resources needed to be brought from Earth. Carbon dioxide in the Martian atmosphere is seen as an unlimited and (fairly) easily extracted source of feedstock for rocket propellant for launch back to Mars orbit in some rocket chemistries also making use of presumed Martian water (to produce methane and oxygen). Crew in Martian bases will also require water and oxygen, which is presumed available in some places on Mars' surface from subsurface sources (and also in Mars' ice-caps during winter). An important activity over the next 10-20 years will undoubtedly be to explore Mars' surface and near-subsurface to develop a better understanding of the locations and extent and form of water resource deposits.

(3) Possible Mission Opportunities

There exist numerous potential future opportunities for Canadian contributions to commercial robotic missions aimed at resource prospecting. NASA's Resource Prospector mission is in the pre-formulation stage and "aims to be the first mining expedition on another world". A Canadian contribution to this mission has been sought in the past and should be discussed and pursued again to capitalize on Canadian pre-eminence in mineral exploration. Canadian-led micro-satellite missions to the Moon and asteroids are also deemed feasible within the scope of the CSA budget.

(4) Investigations

All the proposed investigations under Objective PGGP-01 are also appropriate for Objective PGGP-02. In addition, there are a number of potential instruments that could be developed. Examples include: spectroscopy capable of mapping and characterizing the distribution of water ice at the surface or near subsurface of planetary bodies, e.g. neutron spectroscopy; and gravimeter and tomographic radar to prospect for ore deposits.

3.3.3.1 Summary for Objective PGGP-02

3.3.3.1.1 Canadian Science Roadmap

As with Objective PGGP-01, a series of investigations have been proposed that, if implemented, would result in a radical increase in research conducted by Canadian scientists. Priorities are the two following low-cost grants programs: a new Canadian Analogue Research Program, and a data analysis program for analysis of planetary mission data and samples. Regular opportunities to propose and develop new science instruments aimed specifically at this objective is also critical. This is particularly important for this objective that has a very small and nascent Canadian community but a huge potential, given the world-class terrestrial mineral exploration and mining communities. Initiatives to foster collaboration between the terrestrial mining and space communities will be important to ensure Canada plays a leading role in resource prospecting and exploration in the Solar System.

3.3.3.1.2 Canadian Science Capacity

At the Department of Earth and Atmospheric Sciences U. of Alberta, there is expertise in ore petrology sample analysis and meteorite studies for insights into the economic potential of asteroids. Main areas of expertise include meteorite sample analysis (Herd), northern resources (Pearson), and economic geology (Richards). At Western, there is similar expertise in ore petrology (Banerjee, Linnen, Osinski), petrophysical and meteorite studies (Bouvier, Flemming, McCausland, Osinski) for insights into the economic potential of asteroids. The ROM (Tait) is in an unique situation to study planetary materials directly with the extensive economic geology samples. U. of Winnipeg, York U. and the ROM are involved in the OSIRIS-REx asteroid sample return mission whose objectives include assessing resource potential of near-Earth asteroids. There is also considerable expertise across the country in terms of terrestrial mining and mineral exploration that could be engaged to propel Canada to the forefront of this research internationally.

3.3.3.1.3 Enabling Canadian Technologies

A range of spectrometer and imaging capabilities exist within Canadian industry – both space and terrestrial - that can play a key role in the prospecting and characterization of volatile (particularly water ice) and mineral resources on planetary surfaces, including for example, NIR Raman, APXS, Neutron and X-Ray spectrometry, and indeed Canada can claim world-leading capabilities in each of these areas in the terrestrial sector. In terms of contextual imaging capabilities, in support of Objective PGGP-02, a range of capabilities exist across Canadian industry, for example MDA, Neptec, Honeywell, Canadensys, UTIAS-SFL, Parallax Imaging, MPB and ABB. A number of Canadian organizations have also developed enabling technologies for micro/nano orbiter and/or surface mission elements that present affordable options for Canada to make near term progress in addressing this objective. Gedex Systems Inc. has a strong space systems development expertise. In conjunction with the Space Flight Laboratory at the U. of Toronto, Gedex has developed initial preliminary designs for several deep-space microsat-class missions directed towards asteroid exploration, with the long-term objective of searching for exploitable natural resources. The latest and most advanced of these is the GRavitational Asteroid Surface Probe (GRASP) asteroid lander/rover designed to conduct global gravity surveys on small asteroids, both for scientific purposes and to prospect for potentially valuable ore bodies.

3.3.4 PGGP-03: Understand the origin and distribution of volatiles on the terrestrial planets and their moons asteroids and comets

(1) Objective and Rationale

Many of the questions we seek to answer in Earth and planetary sciences are related to volatile elements such as hydrogen, carbon, nitrogen and oxygen. These elements make up the atmospheres of terrestrial planets and directly affect climate and habitability, in addition to being the building blocks of life as we know it. Our solar system presently has two planets in the Habitable Zone: Earth and Mars. These planets, if given the correct atmospheric conditions, are capable of supporting liquid water at the surface; however only Earth currently has stable liquid water at its surface [1]. If we are to understand how habitable worlds arise and evolve, we also need to study geological-timescale cycling of volatiles through planetary-scale systems. Volatiles were delivered to the Earth in the minerals that make up meteorites and other solar system objects, and were subsequently redistributed by processes such as planetary degassing, to form atmospheres recycling of volatiles through plate tectonic processing and planetary core formation. Another very important part of the rationale for studying this is the potential to use water found on other bodies in the Solar system as a resource to enable other activities carried out in space. That however is dealt with under Objective PGGP-04.

(2) Current State of Knowledge and Knowledge Gaps

H2O is not currently stable anywhere on the surface of Mars in liquid form. Water ice is stable and exposed at the surface in north polar ice cap and underlying the permanent carbon dioxide ice cap at the Martian south pole ([2]), and is stable at shallow depth in the permafrost. There are reasons to suggest that large volumes of ice did or still do occur in the shallow subsurface in the Martian mid-latitudes, and at high elevations approaching the equator or even at lower latitudes during periods of high obliquity. In addition to Mars, several other Solar System bodies are thought to contain ice in the near-subsurface. Radar bright features with similar properties to the icy satellites have been discovered near Mercury's north pole ([3], [4]) and south pole [5]. Like Mercury, the Moon also has large regions of permanently shadowed areas in depressions near the poles. Of the permanently shadowed regions identified, some do appear to have enhanced radar returns [6], but many others do not. These include Cabeus crater, where the LCROSS impactor discovered a few wt. % water ice [7] and Shackleton crater [8] where the Clementine bistatic investigation claimed to have evidence of ice [9].

Volatiles also play a critical role in planetary interiors. Even in exceedingly small concentrations, they strongly influence the rheology, electrical conductivity and melting temperatures of silicate mantles so that convective vigour, and the development of plate (and other) tectonics is affected by the volatile elements that create defects in high pressure mineral phases. High-pressure experimental investigations can constrain the nature of planetary volatiles and predict their distribution within the internal reservoirs of differentiated planets. Our current state of knowledge does not allow us to confidently extrapolate flow laws to the interiors of planets other than Earth, so experimental investigations of planetary analogues are critically required. The secondary atmospheres of terrestrial planets are created by outgassing of planetary interiors, so the nature of such atmospheres, and thus planetary habitability, is dictated by reactions within the interior. In particular, we need to know the solubilities of volatile species such as H2 CH4 and NH4 in planetary magmas under conditions relevant to the terrestrial planets, and to understand the effects of parameters such as oxidation state on volatile speciation if we are to understand planetary degassing. The answers to questions such as how Mars was able to sustain a greenhouse sufficient to allow liquid H2O at the surface will come from an improved understanding of planetary degassing.

The tools that allow us to investigate volatile components of both extraterrestrial samples and the products of experiments on planetary analog materials are vibrational spectroscopies such as IR and Raman, together with microbeam techniques, such as secondary ion mass spectrometry and elastic recoil detection analysis. While significant expertise in these techniques exists in Canada, analysis of light elements and in particular, hydrogen at trace concentrations, is challenging. To compete with current state-of-the-art analytical facilities in the US, we must develop low-blank H analysis in existing Canadian microbeam facilities and obtain well-characterised analytical standards for planetary materials.

(3) Possible Mission Opportunities

NASA's NeMO, scheduled for launch in 2024 is the nearest-term opportunity to address this objective for Mars. As defined in the MEPAG NEX-SAG, polarimetric radar imaging to characterize ice within a few meters of the surface is considered a critical contribution, and Canada has substantial expertise both on the science and engineering side (see Investigation PGGP-03-01 below). ESA's BepiColombo mission would explore Mercury's poles following up on the results of NASA's Mercury Surface, Space Environment, Geochemistry, and Ranging (MESSENGER) mission. Finally, multiple planned missions to the Moon (e.g. Lunar Flashlight Resource Prospector) are focused on identifying volatiles near its poles.

3.3.4.1 Investigations

Many of the proposed investigations under Objective PGGP-01 are also appropriate for Objective PGGP-03. In addition there is one additional proposed investigation described below.

3.3.4.2 PGGP-03-01: Instrument Investigation: Multispectral LiDAR for Mars for the detection and monitoring of atmospheric phenomena and seasonal H2O and CO2 surficial ices/frosts

3.3.4.2.1 Measurement Needs for Instrument

Implementation of both a spatially and spectrally improved laser altimetry orbital instrument that employs a multispectral LiDAR system is not only prudent but highly desirable to both the Mars and broader scientific communities. A multi-laser or tuneable laser system sensitive to 1435 nm and 1500 nm for the identification and discrimination of CO_2 and H_2O ices (e.g. [10]) respectively, would enable seasonal monitoring during day and night passes, providing one of the most complete and comprehensive maps of these surface materials.

3.3.4.2.2 Science Objectives

Understanding the purity, concentration, distribution and form of H_2O and CO_2 ice on the surface of Mars is not only key for understanding present and past climate/habitability of Mars, but also for future manned exploration where these ices will be necessary for generating breathable air, drinkable water, and even fuel. Every winter, the polar regions of Mars are covered with a seasonal polar ice cap composed of predominately CO_2 ice that extends down to latitudes of approximately ±50° [11], with some patches of ice/frost forming closer to the equator under favourable conditions [12].

3.3.4.3 Summary for Objective PGGP-03

3.3.4.3.1 Canadian Science Roadmap

As with Objective PGGP-01, a series of investigations have been proposed that if implemented, would result in a radical increase in research conducted by Canadian scientists. Priorities are the two following low-cost grants programs: a new Canadian Analogue Research program and a data analysis program for analysis of planetary mission data and samples. A new analogue program is a high priority for this objective, given the vast array of world-class and internationally renowned analogue sites in the Canadian Arctic where studies on volatiles could be conducted. Regular opportunities to propose and develop new science instruments aimed specifically at this objective is also critical. High priority targets and opportunities are on Mars, with the potential for Canada to contribute a radar and multispectral LiDAR.

3.3.4.3.2 Canadian Science Capacity

This objective is related to the work being done at U. of Winnipeg on mapping the surface compositions of airless bodies and Mars using reflectance spectroscopy. This work in this area involves a mix of analysis of spacecraft observational data field work at analogue sites and laboratory experiments. In the Department of Earth and Atmospheric Sciences U. of Alberta and the ROM, there is expertise in sample analysis and meteorite curation related to volatiles, including the world's only cold curation facility (Herd) and pristine specimens of the Tagish Lake meteorite (Herd, Tait). At Western the three main groups related to this area is work on volatiles in meteorites and Apollo samples (Bouvier, Osinski, Flemming, McCausland), experimental petrology (Secco, Shieh, Withers), planetary radar (Neish, Osinski, Tornabene, Wang), and glacial and periglacial processes (Osinski, Soare, Tornabene).

3.3.4.3.3 Enabling Canadian Technologies

A range of spectrometer capabilities exist within Canadian industry – both space and terrestrial - that can play a key role in the prospecting and characterization of volatiles. As noted above, radar and multispectral LiDAR are two priority instrument opportunities, and Canada has significant expertise in both these techniques. Importantly Canada has flown both radar and LiDAR in space.

3.3.5 PGGP-04: Determine the interior structure and properties of the terrestrial planets and their moons, icy satellites and asteroids

(1) Objective and Rationale

This objective will focus on several key aspects of the interior structure and evolution of the terrestrial planets, moons and asteroids. Interior structure provides a unique window into the formation of these bodies. It can elucidate the thermal volcanic and tectonic evolution of the body and hence, the geological record preserved in the surface as well as present and past surface modification processes. Interiors are a source and sink for volatiles and thus exert major controls on atmospheric evolution, climate history, and their consequences for surface morphology. The bulk composition thermal and rotational evolution of a planet moon or large asteroid determines its ability to generate a global-scale magnetic field either today or in the past, and together with the volatile history, plays a possibly important but poorly understood role in planetary habitability. On icy satellites, the interior structure determines its ability to host a subsurface ocean of liquid water, a key requirement for a habitable world. Interior structure also affects the rotational and orbital history of small (~100 km diameter and less) asteroids that in turn, determines the present-day shape and affects the mobility of surface regolith material.

(2) Current State of Knowledge and Knowledge Gaps

Satellite observations of a planet's gravity field and Earth-based or satellite observations of its rotational state, provide information on its first-order interior structure – this has been known for some time; for e.g. Venus, Mars and the Moon (summarized in [1]), and more recently for Mercury ([2]; [3]) icy satellites such as Titan ([4]) and large asteroids such as Vesta ([5]) and Ceres ([6]). Meteorites provide independent additional information on silicate compositions and possible core and mantle evolution of their differentiated parent body. Past magnetic fields are sometimes detected in meteorites and in returned samples offering a window on the past thermal and dynamic history of their parent bodies. Additionally, by characterizing meteorites with varying thermal and shock histories, the formation/differentiation processes and timescale (geochronology) of Solar System objects and their interiors could be better understood. Currently, poorly constrained properties that are key to addressing several other objectives include atmospheric loss processes on Mars and Venus, the volatile content and distribution of volatiles in the interiors of Mars, Mercury and the Moon, and the iron mineralogy and absolute thickness of the silicate crusts of these bodies. In particular, although the surface of Mars has been explored in great detail over the last ~20 years through orbital and lander missions, characterization of its global interior structure is rudimentary, and there have been no ground-based geophysical experiments on any of the lander or rover missions. Recent re-evaluation of the Apollo 17 surface gravimetry data has shown that high resolution digital elevation models, in conjunction with surface gravity measurements, can provide insights into local and regional subsurface structure [7] and hence, into the regional geological history. Little is known about the interior structure of small asteroids: some are likely coherent bodies, e.g. Eros [8], whereas many may be rubble piles, e.g. Itokawa [9] and possibly Bennu [10]. Furthermore, recent studies suggest that some asteroids are volatile-rich and/or exhibit transient periodic outgassing ([11]; [12]), indicating a likely continuum of compositions in the asteroid belt between classic silicate-iron asteroids and comet-like compositions. Finally, the thickness of the water ice crust is unknown on many icy satellites, including most notably Europa [13]. This is needed information for determining exchange processes between the surface and subsurface, a key piece of information in determining the habitability of their subsurface oceans [14].

(3) Possible Mission Opportunities

There are several upcoming missions that provide opportunities for exploring planetary interiors through participation of scientists in science teams. The InSight mission to Mars will launch and land on Mars in 2018, deploying a seismometer and heat flow probe, and also measuring the magnetic field environment. The seismic heat flow magnetic and ancillary environmental data will permit investigations of the planet's interior, including core mantle and crustal structure.

The OSIRIS-REx mission to Asteroid 101955 Bennu will collect orbital data on the asteroid's gravity field, shape, surface composition (2018-2020), and will return a surface sample to Earth in 2023. The Mars 2020 mission will carry an Inertial Measurement Unit (IMU) not specifically designed for science investigations, but studies are currently underway to examine whether the data returned from this mission could be used as gravity survey data. NASA's Europa Clipper mission and ESA's JUpiter ICy moons Explorer (JUICE) mission will investigate the interior structure of the Jovian moons Europa and Ganymede. The missions include ice-penetrating radars to probe the structure of the ice crust and possibly image the water-ice interface. They also include gravity investigations and magnetometers for probing the satellites' magnetic fields. NASA's Discovery-class Psyche mission (2022-2026) will visit the likely metal-rich asteroid to investigate its magnetic field internal structure and surface composition and topography, using multispectral imaging, a magnetometer X-band, gravimetry tracking, and gamma ray and neutron spectrometers. NASA's Resource Prospector Lunar rover mission, if equipped with geophysical instruments, could investigate the shallow to medium depth subsurface. Commercial Lunar lander/rover missions, several of which are planned in the scope of the Google Lunar X-Prize, could be equipped with geophysical instruments such as gravimeters. Other opportunities are provided by upcoming Discovery and New Frontiers mission opportunities.

3.3.5.1 PGGP-04-01: Instrument Investigation: Planetary surface gravimeter

3.3.5.1.1 Measurement Needs for Instrument

- For the VEGA gravimeter: Repeatability: 1 mGal.
- Rover Mounted Gravity Gradiometer (RMGG) instrument: Repeatability: 1 eotvos.
- Both:
    - Integration time per measurement: ~ 10 minutes.
    - Auxiliary data needed: navigational data for each measurement station and topographical data for the entire survey area.
    - Navigational accuracy: 5 m or better.
    - Topographical accuracy: 5 m or better.
    - Traverse length: > 150% of the width of sought anomalies (actual anomalies generally determined post facto).
    - Station spacing along traverses: < 10% of the width of sought anomalies.
    - Number of traverses: very target-dependent but for example 2 traverses perpendicular to a linear target (e.g. a lava tube) constrains depth size and strike direction.
      A spiral survey is one way to seek otherwise-unknown anomalies in an area.

3.3.5.1.2 Science Objectives

There are numerous useful science questions that can be addressed by conducting gravitational surveys on the surface of the Moon. By producing measurements from which a subsurface density distribution can be estimated, science questions relating to the geological structure and composition local to the survey area can be answered, or at least constraints can be set.

3.3.5.1.3 Building on Instrument / Previous Studies

The VEctor Gravimeter/Accelerometer (VEGA) instrument is being developed by Gedex. Breadboarding for proof-of-principle testing was carried out under a recent Lunar Surface Gravity Geophysics Science Definition Study. Gedex is part-way through building a flight-test demonstration VEGA instrument with a financial contribution from a CSA STDP Contribution Agreement. A preliminary design for a RMGG has been developed by Gedex based on its High-Definition Airborne Gravity Gradiometer (HD-AGG) system. That was the subject of a previous prototype development proposal to CSA's Ex-Core program. As with the Moon, surface gravimetric and/or gravity gradiometric surveying on asteroids and Mars can be used to look for subsurface density anomalies. New studies are required in order to explore the feasibility of such instruments.

3.3.5.2 Summary for Objective PGGP-04

3.3.5.2.1 *Canadian Science Roadmap*

As with Objective PGGP-01, a series of investigations have been proposed that if implemented, would result in a radical increase in research conducted by Canadian scientists in this area. Priorities are the two following low-cost grants programs: a new Canadian Analogue Research program and a data analysis program for analysis of planetary mission data and samples. The data analysis program is the highest priority with studies aimed at modelling and experiments being particularly important.

3.3.5.2.2 *Canadian Science Capacity*

At the U. of British Columbia, Johnson is involved in several past, ongoing and future missions, in addition to other expertise (Jellinek). The Department of Earth and Atmospheric Sciences and the Department of Physics at the U. of Alberta (Schmitt, Unsworth) have expertise in the geophysical properties of materials and analysis of subsurface data obtained from geophysical sensing. At Western, several members of the CPSX conduct research related to planetary interiors. There is a core group of researchers who focus on high-pressure mineral physics and experimental petrology of planetary interiors (Secco, Shieh, Withers), and several others who study meteorites and their physical properties with relevance to understanding planetary interiors (Bouvier, Brown, Flemming, McCausland, Moser, Osinski, Wiegert). At the ROM, there are several researchers studying meteorites to understand planetary formation and the timescales involved (Tait, DiCecco, White).

3.3.5.2.3 *Enabling Canadian Technologies*

In terms of contextual imaging capabilities, a range of capabilities exist across Canadian industry; for example MDA, Neptec, Honeywell, Canadensys, UTIAS-SFL, Parallax Imaging, MPB and ABB. Gedex Systems Inc. has a gravity geophysics department with extensive experience in planning, conducting, and analyzing the results of gravitational surveys, including ground gravimetry and airborne gravity gradiometry.

3.3.6 *PGGP-05: Understand the impact, threat and hazards posed by impact events on the Earth and other solar system bodies*

(1) Objective and Rationale

The danger to our planet from asteroid and comet impacts is traditionally thought of in terms of extremely rare kilometre-sized 'dinosaur-killing' impacts (e.g. [1]; [2]). Such large impacts have resulted in at least one mass extinction event in Earth history; namely the Cretaceous – Paleogene mass extinction 66 million years ago ([1]; [2]). While such large impacts have obviously played a major role in the geological and biological evolution of Earth [3], it is now becoming clear that the danger due to smaller more frequent impacts, is more important in its societal and economic effects in the short term. The now-famous bright Russian fireball over the city of Chelyabinsk Russia in Feb 2013 resulting from the arrival of an asteroid only 20 m in diameter ([4]; [5]; [6]) with an energy of 500 kT TNT equivalent, resulted in 1800 injuries/hospitalizations and more than $30M in economic damage in the city of Chelyabinsk. This most recent “small” impact, together with the growing completion of Near Earth Asteroid (NEA) orbits in the sub-km size range, has led to a greater focus on the risks posed by decameter- sized impactors, which impact Earth on decadal timescales (e.g. [7]).

Events such as that which formed Meteor Crater in Arizona 50,000 years ago, release two orders of magnitude, more energy than a nuclear bomb [8], underscoring the contemporary hazard from any such ~50 m-sized impactor. Presently, active mitigation of the impact hazard is occurring through several dedicated telescopic surveys for NEOs; to date over 20,000 NEOs have been detected with more than 90% of the kilometer-sized (civilization ending) impactors having secure orbits.

In addition to the impact hazard from individual large impacts, there is also an in situ hazard to spacecraft from natural and manmade debris. This aspect of the impact threat is commonly referred to as Micrometeoroid and Orbital Debris (MMOD), the former referring to natural (meteoroids) produced from the disintegration of comets and asteroids, and the latter attributable to human-produced debris. The hypervelocity impacts from MMOD cause damage to spacecraft kinetically (cratering mechanical damage), as well as damage to onboard electronics caused by plasma production from extreme hypervelocity (>40 km/s) collisions.

(2) Current State of Knowledge and Knowledge Gaps

Smaller asteroids (<100m) are extremely difficult to find telescopically; surveys which are currently active tend to find the largest asteroids more easily. The Chelyabinsk impactor for example, was undetected telescopically before impact. Thus these small but dangerous bodies can be most usefully studied in a statistical sense through meteor techniques, which successfully and routinely detect and study impactors at small sizes (<10 m). There are several large telescopic surveys active in finding NEOs (Catalina Sky Survey, Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), etc.). No Canadian efforts focussed solely on discovery are presently active; the Outer Solar System Origins (OSSOs) survey (http://www.ossos-survey.org) is the closest such effort, but focused on the outer solar system small body population.

The impact population in the decameter size range remains difficult to estimate (e.g. [9]) even though this is the population most likely to produce the next impact damage at the ground ([10]; [11]). In addition to telescopic surveys, global measurements of fireballs using various optical and acoustic networks can define the flux of smaller impactors [6]. Nevertheless, the actual impact frequency and population of the decameter sized NEA population remains controversial, with more than an order of magnitude spread in contemporary estimates (e.g. [6]; [12]; [13]). This remains a major knowledge gap, both in defining the hazard and in defining the delivery mechanisms of NEAs from the main asteroid belt.

Another knowledge gap is that impact rates through time are poorly constrained; the terrestrial impact record is very poorly constrained with less than a quarter of all craters on Earth having accurate (or any) dates [14]. With Canada's expertise and inventory of meteorite impact structures, this is an area that deserves immediate attention. There is uncertainty in the total mass and flux of meteoroids to Earth (e.g. [15]). From a satellite impact hazard perspective, there is controversy surrounding the velocity distribution of small meteoroids near the Earth, with recent models (e.g. [16]) suggesting a huge largely unmeasured population of slow meteoroid population in the tens to hundreds of micron size range. The meteoroid environment at other planets is largely unknown, though there have been efforts to characterize it directly [17] and indirectly from Earth [18]. The actual flux and size frequency distribution of dust in the inner solar system,, and particularly in the outer solar system [19] remains a serious knowledge gap requiring better in-situ measurements.

The space debris (manmade) environment is dynamic and can change dramatically due to one or more breakup events. As an example, the 2007 Chinese FY-1C anti-satellite (ASAT) test and the 2009 Iridium-33 and Kosmos-2251 collision, significantly elevated the debris environment in LEO, the former dramatically increasing tracked debris by 40% in just a few days (NRC 2011). Presently, almost 20,000 individual pieces of space debris larger than about 10 cm are actively tracked and have known orbits; several orders of magnitude, more objects in the cm-size range, are untracked but pose a significant collision hazard. The major knowledge gap in debris studies remains the cm to tens of cm debris population as a function of altitude at any one time – this is just below the trackable size range, but still large enough to cause serious damage.

(3) Possible Mission Opportunities

Canadian-led microsatellite missions present a near-term mission opportunity.

3.3.6.1 Investigations

Many of the proposed investigations under Objective PGGP-01 are also appropriate for Objective PGGP-05. In addition, there is one additional proposed investigation described below.

3.3.6.2 PGGP-05-01: Preparatory Research: Program to support a Canadian fireball network

3.3.6.2.1 Description of the Investigation

As part of a proposed global fireball network expanding from the existing Australian Desert Fireball Network (DFN), an effort is underway to deploy common camera instruments from the DFN to areas in Canada. No funding has yet been dedicated to this Canadian network.

3.3.6.2.2 Science Objectives

The goal of the Canadian pan-fireball network is to collect meteorite samples with known provenance (i.e. pre-atmospheric orbits). To date, only 26 meteorite falls have had their pre-atmospheric orbits measured, making each additional fall with an orbit an invaluable sample-return opportunity. This ground-based effort would have significant synergies with the Canadian involvement in OSIRIS-REx sample return from Bennu, providing advanced opportunities for Canadian meteorite labs to study fresh meteorite falls with known orbits and develop technical capabilities associated with fresh astromaterial collection. Moreover, each new meteorite fall with known orbit provides information on the geology of different parts of the main asteroid belt, the pre-atmospheric orbit being statistically linkable to particular parts of the main belt through resonance escape mechanisms (e.g. [20]).

3.3.6.2.3 Published Canadians

Canada is a world leader in meteor research with significant observational measurement and modelling programs at Western associated with the CPSX and sponsored largely by NASA. Detailed publications can be found at: http://meteor.uwo.ca/. In space debris research, there is engineering research done in conjunction with the Institute of Air and Space Law at McGill, notably in debris removal and modelling [21].

3.3.6.2.4 Canadian Research Facilities

Meteor measurements in Canada are made with the Canadian Meteor Orbit Radar (CMOR), the Canadian Automated Meteor Observatory (CAMO), and the Southern Ontario Meteor Network (SOMN), all at Western [22].

3.3.6.3 Summary for Objective PGGP-05

3.3.6.3.1 Canadian Science Roadmap

For this objective, priorities are the two following low-cost grants programs that if implemented, would result in a radical increase in research conducted by Canadian scientists in this area: a program to support a national Canadian Fireball Network and a new Canadian Analogue Research program. This fireball program would leverage the Australian-led initiative for a global network that already has Canadian participation in terms of personnel, but not in terms of infrastructure in Canada. As noted above, Canadians are world leaders in meteor research. In the analogue program, studies focused on impact cratering would be a priority. Canada has a long history of impact cratering studies and Canadian scientists remain leaders in this field, particularly in the field study of terrestrial impact craters and follow-on laboratory studies.

3.3.6.3.2 Canadian Science Capacity

Western is actively monitoring bright meteor events with the objective of linking meteorites found on the ground with the parent bodies from which they originate (e.g. [23]). The Meteor Physics group comprises 4 core faculty (Brown, Campbell-Brown, McCausland, Wiegert) and several associated faculty. Special attention is given to impacts from asteroidal bodies temporarily captured by the Earth which occasionally strike our planet as meteors [24]. At the U. of Winnipeg, Cloutis is collaborating with observational astronomers to characterize the composition and physical properties of NEAs, including targets of opportunity (i.e. asteroids that unexpectedly appear in near-Earth space), as well as analysis of meteorites from recent falls (e.g. Chelyabinsk). At Calgary, Hildebrand is active in the search for NEAs. In terms of research on the terrestrial impact cratering record, there exists expertise at the Universities of Alberta (Herd), MacEwan (Walton), New Brunswick (Spray) and Western (Bouvier, Grieve, Moser, Osinski, Tornabene).

3.3.7 PGGP-06 Understand surface modification processes on airless bodies

(1) Objective and Rationale

A planetary surface exposed to the vacuum environment of space will result in a number of changes to its physical and chemical properties. The range of processes that affect airless bodies is commonly termed “space weathering”. An incomplete understanding of these processes is currently the greatest impediment to being able to robustly and reliably determine the physical and compositional properties of planetary surfaces. Closing this knowledge gap involves different approaches including theoretical modeling, laboratory experiments, observations of planetary surfaces by various means (e.g. Earth-based telescopes orbiting telescopes flybys orbiters and landers), and sample return. No one of these approaches is ideal in all situations but collectively contribute to closing the knowledge gap. This knowledge gap has implications, both scientific as well as for exploration (e.g. being able to determine the near surface or bulk mineralogy of an airless body that is “hidden” beneath a space weathered crust) where the accessible surface is not representative of the bulk or subsurface composition.

Understanding space weathering may not seem like the most captivating topic, but it is essential. As an example, asteroid Itokawa, the only asteroid from which a sample has been returned to Earth for analysis by the JAXA Hayabusa-1 mission, was interpreted prior to sample return as being either a primitive body similar to ordinary chondrite meteorites, or a differentiated body similar to certain types of primitive achondrites. This issue was resolved only when the returned sample was analyzed on Earth, proving that Itokawa is a likely parent body of some L-type ordinary chondrites. The obscuring effects of space weathering are seen for multiple bodies. Mapping the surface geology of the Moon and detecting surface deposits of various in situ resources is hampered by the uncertainties introduced by space weathering. For asteroids, many of the taxonomic classes do not appear to have meteorite analogues. Whether this is due to space weathering obscuring their identities, or because they have not delivered meteorites to Earth, is unknown. As mentioned, being able to “see past” space weathering will enable us to better address many important first order science questions.

(2) Current State of Knowledge and Knowledge Gaps

The current state of knowledge indicates that multiple processes affect the surfaces of airless bodies. These include, but are not limited to: vacuum desiccation, thermal cycling, electrostatic charging and dust lofting, implantation of solar wind ions, galactic cosmic rays, and bombardment by objects ranging from large bodies to micrometeorites. It is known that these processes all operate at different relative magnitudes that depend on multiple factors, such as presence/absence of a magnetic field, orbital eccentricity, rotation rate, pole orientation, heliocentric distance, and surface composition. The most obvious way to better understand space weathering is by sample return missions. Even landed missions (such as Rosetta) are not able to fully investigate space weathering effects. However, given the diversity of airless bodies, sample return missions from all of them (which would ideally include acquisition of surface and subsurface samples), is not practical. For this reason supporting the plethora of approaches listed above that can help to understand space weathering is essential.

(3) Possible Mission Opportunities

The importance of understanding surface modification processes on airless bodies can be seen by the international interest in sample return missions. NASA, ESA, JAXA, Roscosmos, China and India are all pursuing sample return missions from the Moon and/or asteroids, and one of the primary goals of the asteroid missions is to better understand space weathering. Given this international interest and the fact that one or even a few missions will not help us fully understand or address, space weathering suggests that flight opportunities for Canadian instruments and scientists will be significant in the future.

3.3.7.1 Investigations

Many of the proposed investigations under Objective PGGP-01 are also appropriate for Objective PGGP-06.

3.3.7.1.1 Canadian Science Roadmap

For this objective, priorities are similar as for the previous five; namely preparatory activities and data analysis activities and instrument development programs.

3.3.7.1.2 Canadian Science Capacity

At U. of Winnipeg Cloutis is a member of three NASA Solar System Exploration Research Virtual Institutes (SSERVIs) that are focused on this issue (Remote In Situ and Synchrotron Studies for Science and Exploration (RIS4E), Center For Lunar and Asteroid Surface Science (CLASS), and Toolbox for Research and Exploration (TREX)). This work includes laboratory experiments and analysis of observational data for a wide range of bodies. In addition, one of the major goals of the OSIRIS-REx mission is to better understand surface modification processes on asteroids via sample return. This mission involves additional researchers from the ROM, U. of British Columbia, the U. of Calgary, and York U. At the U. of Alberta, there is a wide range of expertise in remote sensing and sample analysis. This includes the largest University-based meteorite collection in Canada, including samples of a variety of asteroid types, as well as meteorite samples from the Moon and Mars. The ROM is active in using terrestrial samples to compare planetary processes and has one of the largest meteorite collections in Canada, including the largest Howardite-Eucrite-Diogenite collection thought to be from the Asteroid Vesta.

3.3.7.1.3 Enabling Canadian Technologies

As with many of the previous objectives, a range of capabilities exists across Canadian industry in terms of science instruments.

3.3.8 Planetary Geology Geophysics and Prospecting Roadmap

As noted at the outset of this chapter, Canada encompasses one of the most diverse geological records on the planet. This has provided motivation for over 150 years to the pursuit of geological and geophysical investigations across the country. The result is that Canadian scientists are recognized worldwide for expertise and innovation in field-based geological mapping and prospecting, geophysical surveying and modeling, and laboratory-based studies of rocks and minerals. In the latter half of the 20th century, and increasingly in the 21st century, Canadian scientists have expanded their studies to include planetary objects throughout the Solar System. There is also significant synergy and common ground with the Planetary Atmospheres and Astrobiology TTs.

Through broad consultation, the community has identified 6 objectives for *Planetary Geology Geophysics and Prospecting*. Investigations have presented for each of these objectives, with a major emphasis on preparatory research instrument development and data analysis programs. It is noteworthy that many of the proposed instruments are applicable to multiple objectives and multiple planetary bodies, providing an excellent opportunity to fly instruments more than once and for multiple purposes. In addition, many of these instruments are suited to commercialization for the terrestrial market.

Two key cross-cutting Investigations have been identified that are common to and would support all 6 objectives; namely the re-initiation of a Canadian Analogue Research Program (Preparatory Research Investigation), and the development of a data analysis program for the investigation of planetary mission data and samples (Data Analysis Investigation). These investigations offer an opportunity for the CSA to rapidly and significantly bolster the Canadian *Planetary Geology Geophysics and Prospecting* community – and for a very modest budget.

In addition to the Investigations outlined above, there is an urgent need to support capacity building. This community has seen the loss of key professors and a significant number of students to other countries. In order to retain these scientists and in parallel, to increase the experience of Canadian scientists in missions, this community urges the CSA to substantially expand support for mission Co-Investigators and Participating Scientists for spacecraft exploring any target of interest in the solar system (primarily led by foreign space agencies). In addition to an analogue grants program, funding for end-to-end analogue missions, as was provided once in the 2008/2009 timeframe, are requested as they have proven very effective as a training ground for HQP. An increased cadence for instrument concept studies, definition studies, and flight opportunities is the critical ultimate objective. A revivification of a program similar to the CSA Cluster program for HQP training (2012-2015) would also be highly effective at focusing effort of developing HQP and topical research, as was done quite effectively for the ASTRO program under this previous CSA initiative (www.astromaterials.ca).

In terms of instrument development, we require a series of open calls for new ideas. Payload and micro mission concept studies are also a high priority. Technologies that can be applied to mining and mineral exploration should be encouraged. The community deems participation in NASA New Frontiers and Discovery opportunities as absolutely critical. We consider it highly desirable for Canada to develop the capability to fly at least some planetary missions independently of other space agencies in the form of small and microsatellites.

In order to build the overall Canadian community, funding needs to be directed to universities to build critical mass. While funding for undergraduate and graduate students is viewed as important, there is a critical void in support for postdoctoral fellows and entry level (i.e. assistant) professorships. The reinstatement of the former CSA Space Science Fellowships would enable the hiring of new Assistant Professors, which is a critical issue for the community, along with funding for postdoctoral fellows. Funding to support community building in the form of workshops and national networks is proposed. Most of the Canadian *Planetary Geology Geophysics and Prospecting* community could be represented in an expanded *Canadian Lunar Research Network*, which is a part of NASA's SSERVI.

3.3.9 References

- *3.3.2 PGGP-01: Document the geological record and processes that have shaped the surface of the terrestrial planets, their moons, icy satellites and asteroids*

[1] *Head J.W. Mustard J.F. Kreslavsky M.A. Milliken R.E. Marchant D.R. 2003. Recent ice ages on Mars. Nature 426 797–802.*
[2] *Heck, P.R., Schmitz, B., Bottke, W.F., Rout, S.S., Kita, N.T., Cronholm, A., Defouilloy, C., Dronov, A. and Terfelt, F., 2017. Rare meteorites common in the Ordovician period. Nature Astronomy, 1, 0035*
[3] *Herd C.D.K. Hilts R.W. Skelhorne A.W. Simkus D.N. 2016. Cold curation of pristine astromaterials: Insights from the Tagish Lake meteorite. Meteorit. Planet. Sci. 51 499–519. doi:10.1111/maps.12603*
[4] *Osinski G.R. Léveillé R. Berinstain A. Lebeuf M. Bamsey M. 2006. Terrestrial analogues to Mars and the Moon: Canada's role. Geosci. Canada 33 175–188.*
[5] *Osinski G.R. Pierazzo E. 2012. Impact Cratering: Processes and Products. Wiley-Blackwell.*
[6] *Pieters et al. 2011*
[7] *Bland et al. 2016*
[8] *Wilson L. 2009. Volcanism in the Solar System. Nat. Geosci. 2 389–397.*
[9] *Shalygin et al. 2015*
[10] *Hauber et al. 2011*
[11] *Lopes et al., 2013*
[12] *Carr 2006*
[13] *Soare et al. 2011*
[14] *Head et al., 2003*
[15] *ISEC-G white paper*
[16] *J. Borovicka P. Spurny P. Brown P. Wiegert P. Kalenda D. Clark L. Shrbeny (2013) The trajectory structure and origin of the Chelyabinsk asteroidal impactor Nature 503 235-237*
[17] *D. Clark P. Spurny P. Wiegert P. Brown J. Borovicka E. Tagliaferri and Lukas Shrbeny (2016) Impact Detections of Temporarily Captured Natural Satellites Astronomical Journal 151 135-149*
[18] *Clark D. &Wiegert P. 2011 Searching for Serendipitous Meteoroid Images in Sky Surveys in Meteoroids: The Smallest Solar System Bodies Proceedings of the Meteoroids Conference held in Breckenridge Colorado USA May 24-28 2010. Edited by W.J. Cooke D.E. Moser B.F. Hardin and D. Janches. NASA/CP-2011-216469. p.313*
[19] *Abe S. et al. (2006) Mass and local topography measurements of Itokawa by Hayabusa Science 312 1344–1347 doi:10.1126/science.1126272.*
[20] *Ermakov A. I. M. T. Zuber D. E. Smith C. A. Raymond G. Balmino R. R. Fu and B. A. Ivanov (2014) Constraints on Vesta's interior structure using gravity and shape models from the Dawn mission Icarus 240 146-160.*
[21] *Hauck S. A. II Margot J.-L. Solomon S. C. Phillips R. J. Johnson C. L. Lemoine F. G. Mazarico E. McCoy T. J. Padovan S. Peale S. J. Perry M. E. Smith D. E. and Zuber M. T. (2013). The curious case of Mercury's internal structure. J. Geophys. Res. Planets **118** 1204–1220 doi:10.1002/jgre.20091.*
[22] *Hergenrother C. W. et al. (2013) Lightcurve color and phase function photometry of the OSIRIS-REx target Asteroid (101955) Bennu Icarus 226 663–670 doi:10.1016/j.icarus.2013.05.044.*
[23] *Margot J. L. Peale S. J. Solomon S. C. Hauck S. A. II Ghigo F. D. Jurgens R. F. Yseboodt M. Giorgini J. D. Padovan S. and Campbell D. B. (2012). Mercury's moment of inertia from spin and gravity data. J. Geophys. Res. 117 E00L09 doi:10.1029/2012JE004161.*
[24] *Miller J. K. A. S. Konopliv P. G. Antreasian J. J. Bordi S. Chesley C. E. Helfrich W. M. Owen T. C. Wang B. G. Williams and D. K. Yeomans (2002) Determination of shape gravity and rotational state of Asteroid 433 Eros Icarus 155 3-17 doi:10.1006/icar.2001.6753*
[25] *Park R. S. A. S. Konopliv B. G. Bills N. Rambaux J. C. Castillo-Rogez C. A. Raymond A. T. Vaughan A. I. Ermakov M. T. Zuber R. R. Fu M. J. Toplis C. T. Russell A. Nathues and F. Preusker (2016) A partially differentiated interior for (1) Ceres deduced from its gravity field and shape Nature 537 doi:10.1038/nature18955 515-517.*
[26] *Rivkin A. S. and J. P. Emery (2010) Detection of ice and organics on an asteroidal surface Nature 464 1322-1323 doi:10.1038/nature09028.*
[27] *Sohl F. and Schubert G. (2015) Interior Structure Composition and Mineralogy of the Terrestrial Planets In Treatise on Geophysics (Second Edition) edited by Gerald Schubert Elsevier Oxford 23-64 http://dx.doi.org/10.1016/B978-0-444-53802-4.00166-4.*
[28] *Sugita S. Kuroda D. Kameda S. et al. (2013). Visible spectroscopic observations of Asteroid 162173 (1999 JU3) with the Gemini-S telescope Lunar and Planet. Sci. Conf. Abstract 2591.*
[29] *Urbancic N. R. Ghent C. L. Johnson S. Stanley D. Hatch K. A. Carroll W. B. Garry and M. Talwani (2017) Subsurface density structure of Taurus Littrow Valley using Apollo 17 gravity data J. Geophys. Res. Planets submitted.*

- *3.3.2.1 PGGP-01-01: Preparatory Research*

[1] *Osinski G.R. Léveillé R. Berinstain A. Lebeuf M. Bamsey M. 2006. Terrestrial analogues to Mars and the Moon: Canada's role. Geosci. Canada 33 175–188.*

- *3.3.2.2 PGGP-01-02: Preparatory Research*

  [1] *Herd C.D.K. Hilts R.W. Skelhorne A.W. Simkus D.N. 2016. Cold curation of pristine astromaterials: Insights from the Tagish Lake meteorite. Meteorit. Planet. Sci. 51 499–519. doi:10.1111/maps.12603*

- *3.3.2.3 PGGP-01-03: Instrument Investigation: Development of radar and its deployment on missions to map planetary surfaces*

  [1] *Campbell et al. 2004*
  [2] *Paillou et al. 2006*

- *3.3.2.4 PGGP-01-04: Instrument Investigation: Development of LiDAR systems for the surface and orbital characterization of planetary surfaces*

  [1] *Smith et al. 2001*
  [2] *Smith et al. 2010*

- *3.3.2.5 PGGP-01-05: Instrument Investigation: In situ mineral XRD for characterization of mineralogy and mineral resources on planetary surfaces*

  [1] *Bramble M.S. Flemming R.L. and McCausland P.J.A. (2015) Grain size measurement from two-dimensional micro-X-ray diffraction: Laboratory application of a radial integration technique. Am. Mineral. 100 (8-9): 1899-1911.*
  [2] *Izawa M.R.M. Flemming R.L. Banerjee N.R. and McCausland P.J.A. (2011) Micro X-ray diffraction (μXRD) assessment of shock stage in enstatite chondrites. Meteoritics and Planet. Sci. 46 (5): 638-651.*
  [3] *Pickersgill A.E. Flemming R.L. and Osinski G.R. (2015) Toward quantification of strain-related mosaicity in shocked lunar and terrestrial plagioclase by in situ micro-X-ray diffraction. Meteoritics and Planet. Sci. 50 (11): 1851-1862.*
  [4] *Flemming R.L. (2007) Micro X-ray Diffraction (μXRD): A versatile technique for characterization of Earth and planetary materials. Can. J. Earth Sci. 44 (9): 1333-1346.*
  [5] *Osinski G.R. (2007) Impact metamorphism of CaCO3-bearing sandstones at the Haughton structure Canada. Meteoritics and Planet. Sci. 42 (11): 1945–1960.*
  [6] *Flemming R.L. McCausland P.J.A. Gellert R. (2009) In Situ X-ray diffraction on the Moon Mars and asteroids. 40th Lunar and Planetary Science Conference Abs. #1888 Houston Texas (March 23-27).*
  [7] *Vinet N. Flemming R.L. and Higgins M.D. (2011) Crystal structure mosaicity and strain analysis of Hawaiian olivines using in situ X-ray diffraction. Am. Mineral. 96 (4): 486-497.*

- *3.3.2.6 PGGP-01-06: Instrument Investigation: Raman spectrometer for planetary exploration*

  [1] *Skulinova et al. 2014*
  [2] *Brendt C. Hyde, James M. D. Day, Kimberly T. Tait, Richard D. Ash, David W. Holdsworth and Desmond E. Moser. (2014). Characterization of weathering and heterogeneous mineral phase distribution in brachinite Northwest Africa 4872.Meteoritics and Planetary Science. 49(7): 1141-1156.*

- *3.3.2.7 PGGP-01-07: Instrument Investigation: 3D microscope for planetary exploration*

  [1] *Coulter A. B., Osinski G. R.*, Dietrich P., Tornabene L. L., Daly M., Doucet M., Kerr A., Robert M., Talbot M., Taylor A., Tramblay M. 2013. Demonstrating the geological applications of a three-dimensional multispectral microscopic imager (TEMMI) (abstract #2398). 44th Lunar and Planetary Science Conference. Houston, Texas, March 2013 (poster).*
  [2] *Ryan C. H., Haid T. M., Osinski G. R., and Tornabene L. L. 2016. 2015 CanMars MSR Analogue Mission: The utilization of the Three-Dimensional Exploration Multispectral Microscopic Imager (TEMMI) for in situ analysis (abstract #1991). 47th Lunar and Planetary Science Conference. Houston, Texas, March 2016 (poster).*

- *3.3.2.8 PGGP-01-08: Instrument Investigation: Improved APXS for Mars Moon and Asteroids*

  [1] *Gellert, R. & Clark, B. C. (2015). In Situ Compositional Measurements of Rocks and Soils with the Alpha Particle X-ray Spectrometer on Nasa's Mars Rovers. Elements, 11 (1), 39-44, doi: 10.2113/gselements.11.1.39.*
  [2] *Taylor and McLennan 2009*

- *3.3.3 PGGP-02: Determine the Resource Potential of the Moon Mars and Asteroids*

  [1] *Lewis 2015*

- *3.3.4 PGGP-03: Understand the origin and distribution of volatiles on the terrestrial planets and their moons asteroids and comets*

  [1] *Kasting et al. 1993*
  [2] *Carr 1996*
  [3] *Butler et al. 1993*
  [4] *Slade et al. 1992*
  [5] *Harmon and Slade 1992*

[6] *Spudis et al. 2010*
[7] *Neish et al. 2011*
[8] *Thomson et al. 2012*
[9] *Nozette et al. 1996*
[10] *Fink and Sill 1982*
[11] *Leighton and Murray 1966*
[12] *Schorghofer and Edgett 2005*

- *3.3.5 PGGP-04: Determine the interior structure and properties of the terrestrial planets and their moons, icy satellites and asteroids*

[1] *Sohl and Schubert 2015*
[2] *Margot et al. 2012*
[3] *Hauck et al. 2013*
[4] *Less et al. 2010*
[5] *Ermakov et al. 2014*
[6] *Park et al. 2016*
[7] *Urbancic et al. 2017*
[8] *Miller et al. 2002*
[9] *Abe et al. 2006*
[10] *Hergenrother et al. 2013*
[11] *Rivkin and Emery 2010*
[12] *Sugita et al. 2013*
[13] *Nimmo and Manga 2008*
[14] *Hand et al. 2009*

- *3.3.6 PGGP-05: Understand the impact, threat and hazards posed by impact events on the Earth and other solar system bodies*

[1] *Alvarez et al. 1980*
[2] *Schulte et al. 2010*
[3] *Grieve 2017*
[4] *Borovicka et al 2013*
[5] *Popova 2013*
[6] *Brown et al. 2013*
[7] *Brown et al. 2002*
[8] *Kring 1997*
[9] *Harris and D'Abramo 2015*
[10] *Rumpf et al. 2017*
[11] *Collins et al. 2017*
[12] *Boslough et al. 2015*
[13] *Tricarico 2016*
[14] *Jourdan et al. 2009*
[15] *Plane 2012*
[16] *Nesvorny et al 2010*
[17] *Domokos et al. 2006*
[18] *Wiegert et al. 2017*
[19] *Poppe 2016*
[20] *Bottke et al. 2002*
[21] *Misra, Sharf*
[22] *Brown et al. 2008; Weryk et al. 2013; Brown et al 2010*
[23] *Clark and Wiegert 2011*
[24] *Clark et al. 2016*

3.4 Planetary Space Environment

Community Report from the Planetary Exploration Topical Team on Planetary Space Environment

Table 3-4 Planetary Exploration - Planetary Space Environment Topical Team

Name	Affiliation
Andrew **Yau** (Chair)	University of Calgary
Gareth Perry (Exec. Sec.)	University of Calgary
Stavros Dimitrakoudis	University of Alberta
Ian Mann	University of Alberta
Robert Rankin	University of Alberta
Alan Scott	COM DEV (Honeywell)
Bernie Shizgal	UBC
Jean-Pierre St. Maurice	University of Saskatchewan
Dmytro Sydorenko	University of Alberta
William Ward	University of New Brunswick

3.4.1 Introduction to Planetary Space Environment in Canada

Space is fundamentally a harsh environment—an environment that is both invisible and dominated by plasma (ionized gas), electric and magnetic fields, and energetic particle radiation. The planetary space environment is no exception: the harsh conditions of the planetary space environment necessitate a robust understanding of the near-planet environments as a prerequisite to enable human exploration as well as advance fundamental knowledge of the solar system.

The overarching goal of planetary space environment science is to advance our knowledge of the *fundamental physics of and connections between* the Sun and planets (and other bodies) in the solar system, and to improve our ability to forecast and mitigate the resulting effects on human and robotic exploration.

In reaching the consensus below on the two prioritized Planetary Space Environment (PSE) scientific objectives, PSE TT members and other participants in the PSE breakout session in the CSEW were cognizant of the following:

- The intrinsic science merits of the prioritized objectives are of paramount importance;
- The objectives must be relevant to the central themes of (a) the fundamental understanding of PSE and related plasma physics, and (b) the impact of planetary space weather effects on both robotic and human space exploration;
- Important connections and complementarity exist between the different objectives;
- Each of the preparatory research activities constitutes an essential and integral component of a larger *innovative* "*ecosystem*";
- Therefore multiple activities need to be supported including many "low-cost" ones.

The two prioritized PSE scientific objectives are:

- PSE-01 To understand the role of magnetic fields, plasma and atmosphere-ionosphere dynamics on the history and evolution of planets and other solar-system bodies
- PSE-02 To understand and characterize the plasma processes that shape the heliosphere and drive planetary and interplanetary space weather and related effects which create hazards to space exploration

Both of these objectives fit under the overarching theme of "life/biology and evolution/history of planets and planetary resources", and they span the underpinning scientific questions of the prioritized investigation objectives and proposed preparatory research activities below.

In the area of development of new instruments and maintenance of capacity for PSE measurement needs, both instrument concept studies and instrument maturation studies constitute high-priority preparatory research activities in the immediate term as do concept studies of micro-satellite missions.

3.4.1.1 Cross-cutting Heritage Instrumentation

The PSE community currently has strong, and in many cases, internationally recognized capabilities in the following instruments and measurement areas. These will naturally serve as high-priority targets for potential instrument maturation studies for improved-version instruments, and concept studies for “next-generation” instruments to address the objectives below. Such instruments may be used to advance several objectives and hence are considered cross-cutting:

Table 3-5 Cross-cutting Heritage Instrumentation

Instruments	Measurements
Fluxgate Magnetometer	DC magnetic field; magnetic field perturbations
Search Coil Magnetometer	AC magnetic field
Radio Receiver	Electromagnetic and radio waves
Low-energy Plasma Analyzer	Low-energy plasma
Energetic Particle Detector	Energetic particle and radiation
UV visible and near infrared imagers	Aurora and airglow emissions
Michelson interferometer	Wind velocities

3.4.2 PSE-01: To understand the role of magnetic fields, plasma and atmosphere-ionosphere dynamics on the history and evolution of planets and other solar-system bodies

In the case of the Moon, the research focus is on several key issues:

- Lunar plasma environment and its regions.
- The Lunar ionosphere - the ionized portion of a planet’s atmosphere (Recent research suggests the Moon may have an ionosphere despite its lack of a detectable atmosphere).
- Lunar dust and dust storms.
- Multi-scale plasma processes in the lunar wake and magnetic anomalies. The lunar wake is the region immediately behind the Moon that is sheltered from the solar wind (charged particles streaming out from the Sun).
- The use of the Moon as an orbiting planetary space environment observatory for solar Earth and near-Earth observations.

In the case of Mars, the focus is on the following issues:

- Magnetic field and sources of magnetic anomalies.
- The structure, dynamics and history of its atmosphere and ionosphere.
- The effects of solar-wind bombardment on the evolution of the planet’s atmosphere and its volatile gases, which are capable of escaping into space.

In addition to the Moon and Mars, the outer planets are becoming increasingly attractive scientific targets for the study of plasma physical processes in the near-planet space environment, and their effects on space exploration, in light of the current NASA Juno and New Horizon missions and similar upcoming missions, e.g. the Europa Lander Mission, JUICE, and proposed missions to Uranus and Neptune.

In the case of Jupiter - which is the largest planet in the Solar System, for example, the focus of particular interests to the Canadian planetary space environment community is on its strong magnetic field and radiation environment. The magnetic fields of Uranus and Neptune are of similar interest particularly since, although weaker than the Jovian one, their inclinations to their respective planets’ rotational axes make their interplay with the solar wind an interesting and thus far understudied effect.

3.4.2.1 PSE-01-01: Outer planets, magnetic field and radiation environment

(Ranking 1st overall)

The magnetic field and radiation environment of the outer planets, particularly Jupiter, Uranus and Neptune, are of significant interest to the Canadian space environment community. Jupiter is the largest planet in the Solar System, more than 300 times larger than the Earth in mass. Surrounded by a system of dust rings and more than 60 moons, we already know something about the characteristics of the gas giant planet itself. Its atmosphere is composed of about 75% hydrogen and 24% helium by mass, with trace amounts of ammonia and other compounds, including methane and water vapor. The planet is bulged around the equator because of its rapid rotation. It is perpetually covered with clouds of ammonia, with its outer atmosphere segregated into several bands at different latitudes, and featuring a persistent anti-cyclonic storm called the Great Red Spot south of the equator.

The current NASA Juno mission is providing the international space exploration community a golden opportunity to explore Jupiter’s interior magnetic field, aurora, radio emissions, and history. Juno carried to Jupiter a suite of nine scientific instruments designed to gather data on Jupiter’s atmosphere, gravity, magnetic field, energetic particle and radiation environment, aurora and radio emissions. It entered the planet’s orbit on July 4 2016 and has been able to collect a vast amount of new information in a series of close flybys to within 4,200 kilometers of the planet (1/17 of the planet’s radius)! Based on the observation data to date, Juno has found ammonia upwelling near the equator that exhibits significant variability in its abundance at depths corresponding to 30 bars (30 times Earth’s atmospheric surface pressure). The measured gravity hints at a more gradual “differential rotation” (difference in rotation speed between the pole and the equator).

Beyond Juno, Jupiter and its moons will be the target of ESA’s JUICE mission. It is an L1 mission of ESA's Cosmic Vision program and is scheduled to be launched in 2022. The spacecraft should enter orbit around Juno by 2030 and around Ganymede by 2033, thus becoming the first orbiter around a moon other than the Earth’s. Its key science goals are to study the emergence of habitable worlds around gas giants and to study the Jupiter system as a whole, as an archetype for gas giants.

Uranus and Neptune have so far been the target of only one flyby mission - Voyager 2, which reached Uranus in 1986 and Neptune in 1989. This dearth of in situ observations contrasts with the constant discovery of similarly-sized exoplanets around other stars. Ice giants may be the most common type of planet according to exoplanetary surveys, but they are the least visited planets in our solar system. This realization has prompted NASA and ESA to consider an orbiter mission to one or both of them in the near future, and there may be a possibility of Canadian participation.

The Jovian Magnetosphere: Early results from the Juno mission show that the measured Jovian magnetic field is both stronger and more structured than current models expect. Contrary to theoretical predictions, this measured magnetic field does not exhibit any perturbations associated with the electrical currents in the high-latitude regions. Likewise, contrary to expectations, the observed intensity variations of the UV aurora do not quite correlate with the fluctuations of the solar wind dynamic pressure.

Another big surprise is the occurrence of protons originating from the planet energized to hundreds of kilo-electron volts and moving away from the planet. At the same time, there are downward beams of electrons in the polar region that are possibly the source for Jupiter’s intense radio bursts, which have long been detected from Earth. The plasma and radio environment of the Jovian planetary space environment has been a high-value target of the PSE community for many years.

Planetary Bodies and the Jovian Magnetosphere: Ever since the Galileo mission in 1995, there have been indications of the presence of subsurface oceans on Ganymede, Callisto and Europa. The time-varying nature of Jupiter's rotating magnetosphere can induce currents on such salty oceans, which in turn generate magnetic fields for those moons. Part of JUICE's mission is to constrain the electrical conductivity and extent of such oceans. This will be particularly challenging in the case of Ganymede, which is known to generate its own intrinsic magnetic field in its metal core, and generates auroras through its interaction with the Jovian magnetosphere. JUICE will study particle precipitation and acceleration in the region between Jupiter and Ganymede, along magnetic flux tubes that connect the two objects.

There is much to learn by missions to the outer planets, and the skills required of the Canadian PSE community to participate in a scientific or engineering capacity are no different from those required for missions to Jupiter.

Neptune and Uranus – Ice Giants: Unlike gas giants, which are comprised mostly of hydrogen and helium, the contribution of those two elements to the total mass of ice giants is no more than 20%. The predominance of solids in their composition hints at a different formation process and of a difference in how their magnetic fields are generated. Voyager 2 found the magnetic dipoles to be off-center in both Uranus and Neptune, with a tilt of 59° from the axis of rotation in the case of Uranus and 47° in the case of Neptune. In addition, there appear to be strong multipolar components superimposed on those magnetic dipoles. These effects cause the planets' magnetospheres to switch from open to closed configurations with daily and yearly periods. The details of magnetic reconnection particle precipitation and plasma transfer to the inner magnetospheres in such environments are largely unknown and will require in situ measurements to resolve. In the case of Neptune, Triton may be a major source of plasma in its magnetosphere.

3.4.2.2 PSE-01-02: Preparatory Research: Solar wind bombardment of the Mars upper atmosphere

(Ranking 2nd overall)

Solar wind interactions and evolution of volatile atmospheric gases: It is believed that the process of solar wind bombardment caused a significant loss of atmospheric constituents over Mars' history. The historical loss of atmospheric volatiles, including water, is estimated to be comparable to the current atmospheric mass of Mars. *In situ* observations of the escape of ions and neutral atoms will enable us to ascertain the possibly key role of atmospheric loss in the evolution of water and other volatiles on the planet.

Mars atmosphere and ionosphere: An important scientific goal in the exploration of Mars is to understand the structure dynamics and history of its atmosphere and ionosphere. Because of the solar wind bombardment, the Martian ionosphere appears to have an entirely different altitude distribution from Earth's ionosphere. On Mars, there is an ionopause where the ionization density drops precipitously over a very short altitude range. The altitude of this ionopause appears to vary in response to changes in the dynamic pressure of the solar wind.

This explains the important connections between ionospheric variability, solar wind penetrations, plasma and atmospheric escape, atmosphere-ionosphere coupling, and atmospheric evolution on Mars. A comprehensive investigation of these connections has been the aim of many past and ongoing Mars missions, and this work will be carried on in future missions.

3.4.2.3 PSE-01-03: Preparatory Research: Lunar plasma environment and regions

(Ranking 3rd overall)

The near-Moon electromagnetic and plasma environment plays a dominant role in the dynamics of the physical processes in different regions of the Moon. An example is the ionization of lunar surface materials by the Sun's extreme UV light, which results in the emission of photoelectrons from the lunar surface, and the electrically positive charging of the surface. On the night side of the Moon, the surface can be negatively charged to a much stronger level than the positively-charged day side - to the point of creating a hazard for both robotic and human exploration activities.

Figure 3-1 is an artist's concept of the plasma environment on the Moon, including its different plasma regions and interactions with the solar wind.

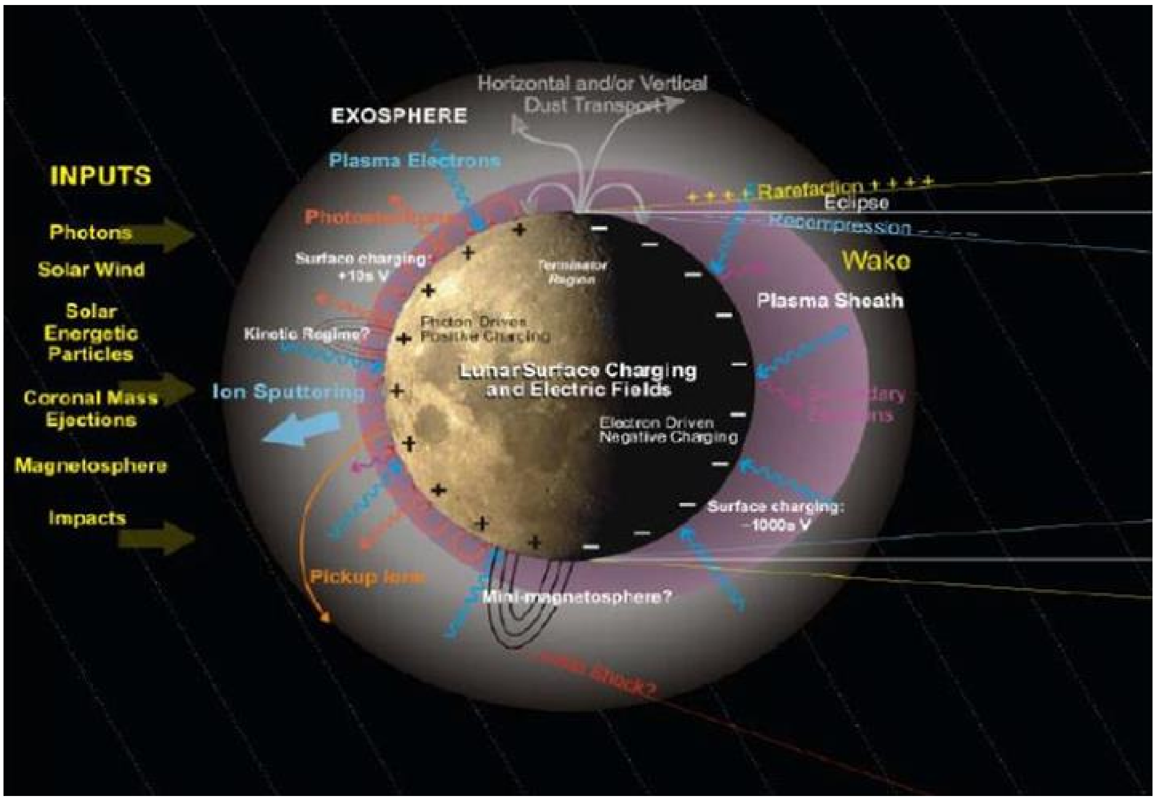


Figure 3-1 Plasma environment and regions on the Moon and interactions with the solar wind [1]

Mini-Magnetospheres: An important element in the near-Moon electromagnetic equation is the "mini-magnetospheres" created by crustal anomalies beneath the lunar surface. These are localized regions of strong magnetic fields on the opposite side of the impact craters on the Moon, up to 50-100 kilometers in altitude above the lunar surface.

They are an excellent research target because of their localized nature and the way they interact with the solar wind to form miniaturized versions of magnetic field structures found on Earth, such as the magnetopause and "bow shock." The magnetopause is the boundary between the interplanetary and the Earth's intrinsic magnetic fields, and "bow shock" is the shock front nearby created by the slowing down of the incident supersonic solar wind.

Lunar mini-magnetospheres are also the only accessible astrophysical plasma for studying plasma physics down to a sufficiently small spatial scale to unravel the properties of plasma at the fundamental level. They are important for magnetic surveys of the Moon. Studying mini-magnetospheres will also pave the way for their potential use as artificial magnetospheres and protective shells to shield astronauts and sensitive equipment from energetic particle radiation on the lunar surface.

Lunar Ionosphere: The Japanese Kaguya lunar orbiter recently revealed the possible existence of an ionosphere on the Moon. The ionization density is more than 100 times greater than expected given the Moon's virtually non-existent atmosphere. Kayuga also unexpectedly observed ions reflected from the Moon. Unlocking the secrets of the lunar ionosphere is an important part of understanding the Moon and its evolution.

Lunar Terminator: The physics of the lunar terminator (the boundary between the day and night sides of the Moon) and the lunar wake are of fundamental interest. The Apollo astronauts reported dust storms at the terminator, which have also been observed frequently by lunar orbiters. The changing electron density across the lunar terminator is expected to generate electric fields which can cause dust storms by accelerating the movement of the charged dust. These storms pose a major challenge to operations on a lunar base (for example making it difficult to maintain a dust-free environment for sensitive sensors and equipment).

Charge separation (the separation between positive and negative charges) in the shadow region of the lunar "plasma wake" is believed to drive a variety of plasma and ultra-low-frequency waves, which will likely influence the transport of plasma in this region. The lunar wake will serve as an analogue environment for later studies of plasma wakes on asteroids and comet tails, where similar plasma processes are believed to operate and play an important role in comet-tail formation. Understanding the effects of the electric and magnetic fields, and the resulting dust dynamics at the lunar terminator and wake, is an important priority for both scientific and operational reasons.

Lunar Dust and Dust Storms: Apollo astronaut Gene Cernan once remarked: "Dust is probably one of our greatest inhibitors to a nominal operation on the Moon." As lunar dust moves around, dust particles on the day side of the Moon are charged positive while those on the night side are charged negative. This creates a "dusty plasma" in which like-charged dust grains can levitate to altitudes up to 100 kilometers on the night-side. The transport of the charged dust, which is affected by electric fields across the lunar surface, poses a hazard to instruments deployed on the lunar surface.

Characterizing the lunar dust environment and studying the related surface charging will allow important comparisons between the lunar environment and other planets and moons, such as Mercury and the Moons of Jupiter. It will also provide the knowledge needed to reduce the adverse effects of dust in lunar surface operations.

Multi-scale Fundamental Plasma Physics: The plasma wake and surface magnetic anomalies on the Moon provide a natural laboratory in which to study the fundamental physics of multi-scale astrophysical plasma (i.e. plasma that varies over multiple spatial and temporal scales). The plasma processes in both the wake and the anomalies are believed to occur over a wide range of spatial and temporal scales; the behavior of the plasma is dominated by both very large scale and very small scale processes. In this way they are similar to many auroral and magnetospheric plasmas of interest on Earth and other planets. Studies of these multi-scale processes will advance our knowledge of the fundamental physics in astrophysical plasmas.

3.4.2.4 PSE-01-04: Preparatory Research: Mars magnetic field

(Ranking 5th overall)

Mars' magnetic field is just as inviting as the Moon's for planetary space environment research. The Mars Global Surveyor mission recently confirmed the very weak or near-non-existent magnetic field on Mars (3000 times weaker than Earth's) and revealed the presence of strong localized sources of crustal magnetic anomalies that are associated with the ancient terrain.

Figure 3-2 is a map of the crustal magnetic field anomalies overlaid with the large craters and the so-called north-south dichotomy boundary, which separates the ancient terrain and highlands to the south from the younger terrain to the north. The presence of the anomalies south of this boundary and their absence over major volcanic edifices and in impact craters, suggest the magnetized crust was destroyed by the impacts, and the magnetic dynamo on Mars probably stopped about 3.9 billion years ago.

Evolution of Mini-magnetospheres: The magnetic dynamo that created a magnetic field on Mars possibly operated for a few hundred million years after the planet was formed before shutting off. Evidently, the formation of the dichotomy boundary postdates the cessation of the dynamo, and localized regions of the ancient magnetized thin crust were modified by deep impacts and magmatic flows (flows of molten rocks below the surface.) Re-heating and tectonics - the movement of rock plates that form the outer crust of Mars equivalent to earthquakes - may also have played a role. Thus, the magnetic anomalies will allow us to study the origin and history of the magnetic field structure and crustal anomalies on Mars, and the potential vestiges of life and water inside the mini-magnetospheres.

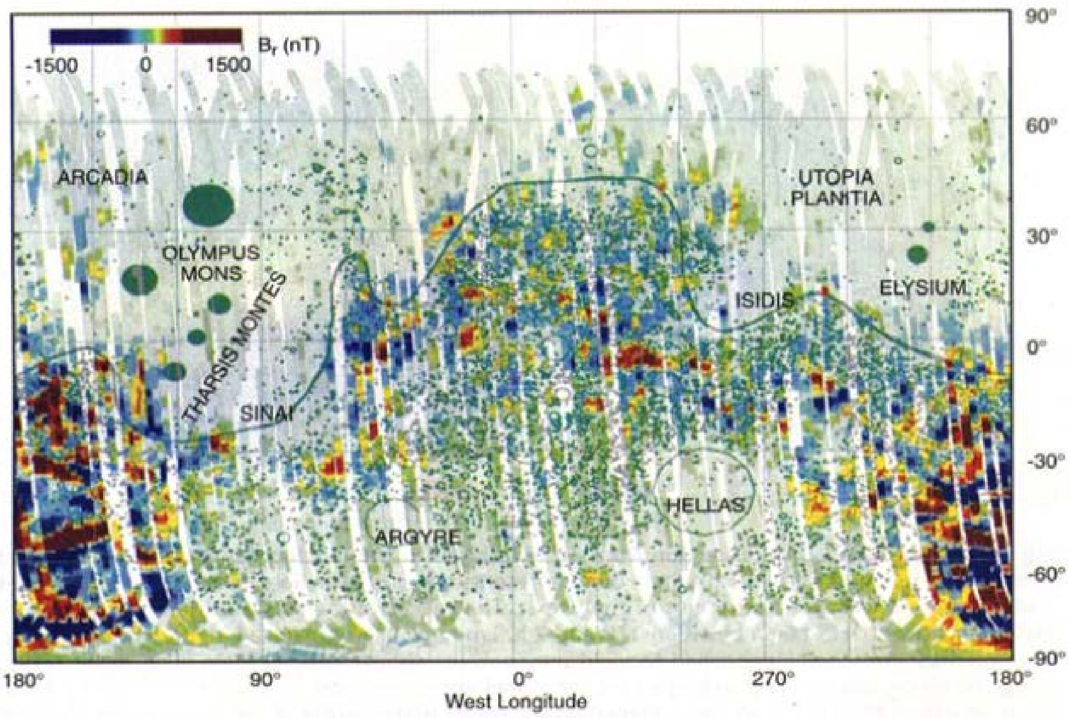


Figure 3-2 Map of crustal magnetic field anomalies on Mars overlaid with the large craters and the north-south dichotomy boundary with the magnetic field strength color-coded

PSE-05: Mars - Solar wind bombardment of the Mars upper atmosphere[2]

In the absence of a strong internal magnetic field, the direct bombardment of the solar wind on Mars' atmosphere energizes the ions in the Martian ionosphere; this enables them to subsequently overcome gravity and escape the atmosphere. They also collide with uncharged (neutral) atoms in the atmosphere causing these atoms to "splash" away from the planet.

3.4.2.5 PSE-01-05: Human exploration enabled: Orbiting lunar observatory

(Ranking 7th overall)

The concept of using the Moon as an orbiting observatory for space imaging and for studying the physics of the solar system (heliophysics) was first proposed by the Canadian space science community in the 1990 Long Term Space Plan. NASA's recent report on heliophysics on the Moon revives interest in using the Moon for imaging the solar surface near-Earth space and the boundaries of the solar system.

The Moon is a perfect remote-sensing platform because it has no atmosphere to absorb incoming radiation and distort measurements. It also has no intrinsic magnetic field, making it ideal to study a variety of key scientific targets including: the composition of the solar wind; the history of solar wind bombardment on the Moon; the Sun; the inner solar system and cosmic rays from outside the solar system.

Magnetic Reconnection: The process of magnetic reconnection occurs when the magnetic lines of force originating from two distinct geophysical regions reconnect and release their stored magnetic energy into particle kinetic energy over a localized region and in an explosive manner. This process is central to the flow of mass and energy between magnetized astrophysical plasma systems, such as the Sun, the Earth, and other magnetized planets (e.g. Jupiter and Saturn).

Coronal Mass Ejection: A Coronal Mass Ejection (CME) is an ejection of energetic plasma from the Sun at speeds up to 10 million kilometers an hour. When a CME reaches the Moon, it can disrupt radio transmissions within the Moon, as well as between the Moon and the Earth, disable Moon-orbiting communications satellites or cause satellite navigation systems to malfunction.

3.4.3 *PSE-02: To understand and characterize the plasma processes that shape the heliosphere and drive planetary and interplanetary space weather and related effects which create hazards to space exploration*

PSE science as pursued under PSE-01 provides the knowledge base to develop an ability to forecast space weather (space situation awareness). This research will also help develop protection measures and mitigation strategies against space radiation and other harmful effects of the space environment. These are prerequisites for both robotic and human exploration in space.

3.4.3.1 PSE-02-01: Preparatory Research: Moon Space radiation: forecast and mitigation

(Ranking 4th overall)

Even at 10,000 meters above the Earth's surface, and despite the protection afforded by the Earth's magnetic field, the harmful effects of energetic particle radiation from the Sun are a serious concern for airline passengers on trans-polar flights. In fact, airlines often alter their flight plans to longer and more costly routes away from the magnetic pole, sometimes when an aircraft is already in the air.

Beyond the Earth's immediate confines, space radiation poses a significant challenge to both robotic and human exploration. For example, the radiation belts surrounding Earth would darken camera lenses and degrade fiber optics cables rendering them unusable in a matter of weeks. Therefore, sensitive equipment must be adequately shielded to reduce the radiation dose to an acceptable level. The same is true for astronauts.

PSE studies will provide the knowledge base for developing protection measures and mitigation strategies against space radiation and other harmful effects of the PSE.

- **Real-time monitoring and forecast of near-Moon space conditions** affecting astronauts on and en-route to the Moon (i.e. space situation awareness).
- Monitoring and real-time broadcast of radiation bombardment events on the lunar surface.
- **Magnetic shields development**: Development of magnetic shields to protect against radiation.

3.4.3.2 PSE-02-02: Preparatory Research: Space weather on Mars

(Ranking 6th overall)

Mars provides an excellent vantage point for monitoring and studying space weather in the inner solar system. At the same time, the safety and success of exploration missions to Mars require forecasting and mitigation of the adverse effects of space weather.

Space weather on Mars - forecast and mitigation: At minimum, this must include real-time monitoring and forecasting of space weather affecting astronauts on and en-route to Mars, and the development of magnetic shields to protect humans and equipment against radiation bombardment on the Martian surface. It is also important to understand and predict the effects of variations in atmospheric density on spacecraft that use aerodynamic braking to reduce speed when going into orbit around Mars or landing on the planet's surface.

3.4.4 Planetary Space Environment Roadmap

To help prepare the PSE community for upcoming mission and scientific opportunities targeted at the two prioritized scientific objectives above, high-priority preparatory research activities deserving the strongest support as part of Canada's commitment to space exploration in the area of PSE include the following:

- Data analysis and modeling studies of current and upcoming PSE missions: e.g. Mars Atmosphere and Volatile Evolution (MAVEN) and the UAE Mars mission; theoretical modeling in dusty plasmas, dynamics of planetary atmospheres and ionospheres, collision processes in planetary exospheres, and mini-magnetospheres;
- New knowledge creation through the development of new mission targets and innovative instruments and the training of the next-generation of HQP;
- Development of new instruments and maintenance of capacity for identified PSE measurement needs applicable to multiple SE missions: e.g. miniaturized fluxgate magnetometer for CubeSat missions;
- Establishment of (Canadian) "Guest Investigator" opportunities for participation in existing SE missions through data analysis and modeling, e.g. MAVEN, New Horizon, JUNO, etc.

3.4.5 References

- *3.4.2.3 PSE-01-03: Preparatory Research: Lunar plasma environment and regions*
  - [1] *Delory et al. 2008/UC Berkeley*
  - [2] *Acuna et al Global Distribution of Crustal Magnetization Discovered by the Mars Global Surveyor MAG/ER Experiment 1999*
- *3.4.2.4 PSE-01-04: Preparatory Research: Mars magnetic field*

  Acuna et al Global Distribution of Crustal Magnetization Discovered by the Mars Global Surveyor MAG/ER Experiment 1999)

4 Space Health in Canada Overview

Community Report from the Space Health Topical Team

Table 4-1 Space Health Topical Team

Name	Affiliation
Gordon Sarty (Chair)	University of Saskatchewan
Andrew Frank-Wilson (secretary)	University of Saskatchewan
Heather Allaway (intl observer)	Pennsylvania State University
Natalie Allen	Western University
Melissa Battler	Mission Control Space Services Inc.
Steven Boyd	University of Calgary
Philip Chilibeck	University of Saskatchewan
Mike Dixon	University of Guelph
Jonathan Farthing	University of Saskatchewan
Paul Fulford	MDA Corporation
Helene Girouard	Université de Montréal
David Hart	University of Calgary
Richard Hughson	University of Waterloo
James Johnston	University of Saskatchewan
Chantal Kawalik	University of Saskatchewan
Saija Kontulainen	University of Saskatchewan
Kris Lehnhardt (intl observer)	George Washington University
Scott McLeod	DND
Ivar Mendez	University of Saskatchewan
Lowell Misener	Calm Technologies Inc
Andre Obenaus	Loma Linda University
Jean-Francois Roy	Hexoskin
Joan Saary	St Michael’s Hospital/University of Toronto
Somaie Salajeghe	University of Saskatchewan
Alan Scott	COM DEV International
Jonathan Sharp	University of Alberta
Kevin Shoemaker	Western University
Garnette Sutherland	University of Calgary
Boguslaw Tomanek	University of Alberta
Krzysztof Turek	MRI-Tech

4.1 Summary

We will evolve into new species on many planets throughout the Galaxy. Our descendants' journeys to other planetary bodies in the Solar System will be long, zero-g trips in small living quarters with a heavy solar and galactic radiation background. The journeys will be hazardous to their health without understanding and mitigating the risks. Our international collaborators, NASA, in the United States, are planning for voyages to the asteroids, Mars and its moons Phobos and Deimos using current rocket technology. So, while future rocket technology may get us to the vicinity of Mars in a few weeks, current plans call for voyages that will take on the order of two years. A large amount of survival technology needs to be developed before such a lengthy trip can be attempted. The Moon is therefore the next logical space exploration destination and our international collaborators, the ESA, in Europe are planning to build a Moon village in the 2030s. Other potential international space exploration collaborators, China and India, also have plans to send humans to the Moon.

The Space Health TT has reviewed the current state of our understanding of space health issues, from the molecular and genetic levels to spacecraft health care systems and Earth-based analogue facilities. From that review, future directions were identified and priorities quantified on the basis of *Scientific Merit* and *Benefits to Canadians*, where we considered both the research community and the larger Canadian society, especially for health care, when we considered Benefits. The review and prioritization of Canadian space health research was organized under four Objectives.

4.1.1 Prioritised List of Objectives

The four Space Health scientific objectives are:

- SH-01: To better understand the risks to living organisms of radiation exposure beyond low-Earth orbit and develop effective countermeasures
- SH-02: To better understand biological and physiological changes that occur in reduced gravity environments and to develop effective countermeasures
- SH-03: To develop a more integrated understanding of the biological and physiological effects of the space environment and develop integrated countermeasures
- SH-04: To better understand the psychological effect of spaceflight and develop effective countermeasures

Aspects of many of the important Research Questions (RQ) appeared under more than one objective, for example food/nutrition, behaviour, exercise, space medicine and the need to complete ground-based research in analogue facilities. Prioritization was quantified first, and a research question level then associated facilities and systems were quantified on the basis of their utility in answering the RQs. In terms of classification by the Objectives, a two-dimensional scatterplot of RQ priorities revealed a loose ranking of the Objectives with the ranking being Objectives SH-03, SH-02, SH-01 and SH-04. However, given the appearance of similar research themes under more than one Objective, such a ranking of Objectives needs to be examined more closely by any reader of this document to see the broader picture.

It is our hope that this document will be useful both for the research community, who need federal resources to pursue their research, and to the CSA who are responsible for allocating those resources.

4.1.1.1 Criteria for Prioritization

The main priorities for the CSA are: Merit, Community and, Benefits to Canada. The prioritization criteria given here reflect those priorities in a way that is suitable for space health systems and facilities.

Within each of the four scientific objectives described in Section 4.1.1, RQs are posed. These RQs are scored in two categories: 1) Merit, and 2) Community and Benefits to Canada. These two categories capture the main priorities for the CSA, similar to how tri-agency grants are scored, particularly the very relevant Collaborative Health Research Project (CHRP) grants awarded by a Canadian Institutes of Health Research (CIHR)/NSERC partnership. Merit scores are given as described in Table 4-2.

Table 4-2 Merit Considerations and Score

M#	Merit Consideration	Score		
		Yes	No	Fuzzy
M1	*Does it fill a gap?*	1	0	Between
M2	*Does it significantly enhance our capabilities?*	1	0	Between
M3	*Does it replace outdated technology?*	1	0	Between
M4	*Are there no alternatives?*	0	1	Between
M5	*Does it duplicate what we already know?*	0	1	Between
M6	*Is there evidence to support investigating or developing it?*	1	0	Between
M7	*Is it unique to a space environment*	0		Between
	or are there terrestrial applications? (e.g. to the health care system)		1	
M8	*Does it have potential to be an incremental advance*	0		Between (if more usual)
	or a quantum leap?		1	
M9	*Do we need it*	3, 2, 1	0[00]	
	or would it be nice to do?			Between
	*** score 3 for research that can be done on the ISS (near term)			
	** score 2 for research that needs to be done on the Moon or in cis-lunar space (intermediate term)			
	* score 1 for research that requires deep-space voyages to Mars or the asteroids (long term)			
	[00] No points if it is not clear how the results of the research will be useful for the anticipated exploration progress from the ISS to the Moon/cis-lunar space, to the asteroids and Mars.			

For Community and Benefits to Canada, scores on a scale of 0 to 5 are given for each of the five questions listed in Table 4-3.

Table 4-3 Community and Benefits to Canada Considerations and Score Criteria

Q#	Question and Score Criteria
Q1	*Does the research encourage the clinical and research communities to work together?* • A higher priority is given if so. • This criterion supports the CSA priority of building community.
Q2	*Is there a socio-economic benefit?* • A higher priority is given if so. • Included in the evaluation of socio-economic benefit is the degree that the operation of a given system or facility required to answer a RQ, or the activity of answering the RQ, will have in inspiring the next generation of Canadians to adopt STEM-based careers. In that respect projects with a future vision that goes beyond what is currently technically possible have more socio-economic benefit. Projects that push the boundaries of what humans can accomplish have long-term socio-economic benefit and contribute to an innovation agenda. • This criterion supports the CSA priority of providing a benefit to Canada.

Q#	Question and Score Criteria
Q3	*Is the required research team Canadian-led?* • Canadian-leadership has a higher priority. • This criterion supports the CSA priority of providing a benefit to Canada.
Q4	*Is the required research team part of an international collaboration?* • International Collaboration both reduces the costs to Canada associated with the research activity and provides Canadians an opportunity to be part of a larger effort that no one country could afford on their own. • The ISS and planned voyages to the Moon, Mars and the asteroids are primary examples of that principle. • This criterion supports the CSA priority of providing a benefit to Canada.
Q5	*Canadian capabilities: is this an established or emerging area of Canadian strength?* • A score of 0.5 is given for an emerging area, 1 for an established area. • Since the objective of space health research is to push the boundaries of what we know, an emerging area is only marginally disadvantaged in priority over an established area especially if a system or facility or activity is judged to be critical to meeting a scientific objective. The past involvement or interest of a Canadian company (see next subsection) with a particular system or facility is a demonstrated Canadian capability. • This criterion supports the CSA priority of providing a benefit to Canada.

With these scores, 0-11 for Merit and 0-5 for Community and Benefits to Canada, a RQ may be placed on a priority plane as shown in Figure 4-1. The CSA could place other RQs, not explicitly identified in this document, on the priority plane in order to assess its priority relative to other RQs. An overall priority score is computed as the Euclidean distance of the priority plane point from the origin. That is:

$$Priority\,score = \sqrt{(Merit)^2 + (Community\,and\,Benefits\,to\,Canada)^2}$$

Identified systems and facilities are scored by summing the priority scores of RQs with which they are associated.

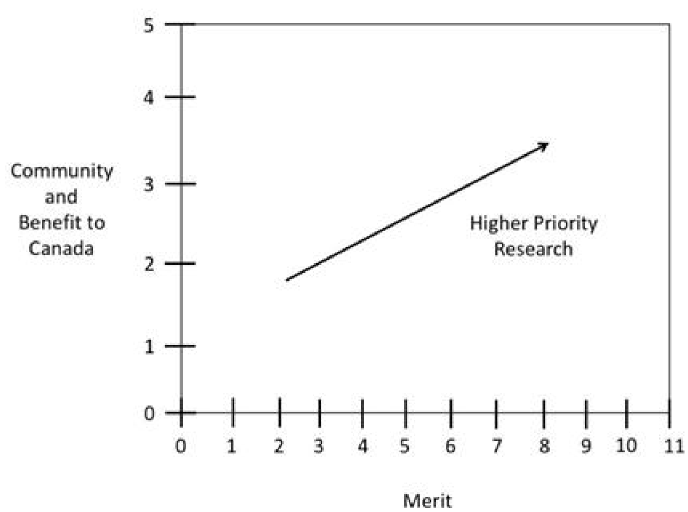


Figure 4-1 Priority Plane. RQs may be prioritized by plotting their scores.

RQs plotted to the right and above other questions have higher priority.

No attempt is made to assess the TRL of a system/measure/facility because the technologies generally advance continuously. The priorities given here therefore represent a starting point for the CSA to make funding decisions, with TRL and risk assessment being made at the time funding decisions are made.

For each research objective, reviews of the current state of the art are provided. Some areas of research, especially neuromuscular research, have a long history that goes back to the first human space flights in the 1960's. Other areas, like robotic surgery and Magnetic Resonance Imaging (MRI), are very new. Our purpose is to be thorough and to give advice on prioritization on the basis of an objective look at what is needed to enable safe, healthy exploration and, ultimately, the colonization of planets in our solar system and other stellar planetary systems in our Galaxy. For the near future, we give priority to systems and facilities that support research on the ISS. For planning and setting up priorities for systems and facilities beyond the ISS, we regard the Moon as the next logical place where sustained space health research can proceed. Journeys to the asteroids and the first steps to Mars will necessarily focus on the exploration mission itself with implementation of proven countermeasures.

Space health research is unique in space exploration science in that most researchers have "day jobs" doing research that is directly applicable to life on Earth. The "spin-in" and "spin-out" aspects of space health research are strong, especially if prioritisation criterion Q2 of the Community and Benefits to Canada category is met. In the next section, we give a brief (necessarily incomplete but reflective of those companies that participated in the Space Exploration TT effort) overview of Canadian companies with interests in human space health research who participated in the TT effort. We also give a list of funding partners and organizations that space health researchers frequently engage with in their "day jobs". There is a very real opportunity for the CSA to partner with these organizations to solve problems that would benefit both the Canadian health care system and Canadian aspirations for human space exploration simultaneously. There is real value to be added here for the Canadian health care system. By working on projects to solve space health problems, solutions to pressing "ordinary" problems will appear. Parallels between the effects of aging and the physiological effects of long duration space flight on astronaut health; as well as the need to develop highly robust portable medical diagnostic equipment with tele-health capacity for operation in remote and rural communities, are two examples where investment in space health research can provide a high return on investment for the Canadian tax-payer.

4.1.2 Context: Partnership Opportunities and Future Direction

A primary message that the Space Health TT regards as important is to point out the opportunities for collaboration and joint funding. Section 4.1.3 gives a list of potential partners for the CSA with whom partnership funding arrangements would produce benefits for both partners. That is, benefits would result from partnerships for both everyday, terrestrial health research and technology and for space health research and technology.

Finally, the Space Health TT wishes to motivate the need for space health research from a broad perspective that gives the whole endeavour meaning. We believe that the tax payer rightfully expects to know why their tax dollars are spent the way they are, so we explicitly articulate the exciting and ultimately meaningful reasons why space health research and related technology development is important in Section 4.1.8. In Section 4.1.8 we also lay the groundwork for the basis of our enumeration of priorities.

4.1.3 Funding partners and organizations with an interest space health related research

The TT identified a number of Canadian organizations that are potential funding partners or supporters. Systems/measure/facilities that could benefit from the involvement of these organizations show a high level of Canadian capability and a potential for the creation of a Canadian-led endeavour. The involvement of the health research organizations CIHR, Canadian Society of Hypertension, Heart and Stroke Foundation and the NCE AGEWELL also encourage the clinical and research communities to work together.

4.1.3.1 Canadian Institutes for Health Research (CIHR)

The *Institutes* with objectives that overlap with space health objectives are listed in Table 4-4.

Table 4-4 Institute Objectives Overlap with Space Health Objectives

Objective	Description
Aging	Of this institute's strategic priorities, the following priorities potentially have overlap with space health science: a. Health care and services that combine and integrate continuity, innovation and efficiency; b. Ensuring the conditions for a positive impact on older people's health and wellness. Both priorities overlap with the psychological objectives (Objective SH-04) of space health science, including remote presence technology such as used by the associated AGEWELL centres of excellence. There is also the concept that exposure to microgravity may serve as a model of accelerated aging for some physiological systems, and as such, may yield knowledge relevant to improved health and longevity on Earth.
Cancer Research	With exposure to radiation, astronauts are at an increased risk of developing cancer later in life. Strategic priorities that focus on innovative research approaches to prevention, detection, monitoring, tailored therapies and care strategies have a potential overlap with space health science objectives, particularly Objective SH-01.
Circulatory and Respiratory Health	The effect of reduced gravity on the cardiovascular system is part of space health scientific Objective SH-02.
Gender and Health	Recent studies on in-flight changes in insulin resistance and arterial stiffness, and hormonal responses indicate that there are sex differences [1], [2]
Genetics	One of the strategic priorities for this institute is to develop computational and systems biology models. Such models are needed to meet the goals of space health Objective SH-01 with respect to the interaction of radiation with human genes and the increased risk of cancer.
Infection and Immunity	There is some interest, under space health Objective SH-02 on how the immune system is affected by microgravity and reduced gravity. Astronaut based investigations could contribute to this institute's interest in environment and health. In particular, studies focused on gut microbiota, alterations in gut microbiota and diet, microbiota alterations in microgravity, and in relation to the immune system integrity, etc. are relevant.
Musculoskeletal Health and Arthritis	The connection between astronaut bone loss and osteoporosis is well known and there is potential to develop a strong relationship between the clinical and research communities if this institute became interested in space health research. Additional areas of potential interest are regulation of muscle atrophy, muscle atrophy and bed rest, sarcopenia/bedrest or microgravity and fatty infiltration of muscle.
Neurosciences, Mental Health and Addiction	The effect of the space environment on the nervous system is relatively unexplored and the understanding of this effect is one of the goals of space health Objective SH-02. It is also known that radiation can affect the nervous system (Objective SH-01). It is also known that exercise can contribute to retention of cognition which links to vascular health and aging.
Nutrition, Metabolism and Diabetes	The effect of the space environment on the nervous system is relatively unexplored and the understanding of this effect is one of the goals of space health Objective SH-02. It is also known that radiation can affect the nervous system (Objective SH-01). It is also known that exercise can contribute to retention of cognition which links to vascular health and aging.

4.1.3.2 Natural Sciences and Engineering Research Council (NSERC)

Joint funding programs between the CSA and NSERC have been supported in the past. We encourage the CSA to reinstitute a collaborative program with NSERC. In addition to the investigator-initiated Discovery grant programs, NSERC also has a series of industrial partner programs (e.g. Engage grants) as well as NSERC-CIHR collaborative program and the CHRP grant program. Institutions involved in space health research can also apply to the Collaborative Research and Training Experience (CREATE) program to establish innovative training environments. These CREATE grants currently support training in other technological areas of interest to the CSA.

4.1.3.3 Social Sciences and Humanities Research Council (SSHRC)

SSHRC have multi agency funding as a focus; they are open to the formation of collaborative funding programs. Funding for understanding the psychological and mission efficiency factors of space flight, space health Objective SH-04, could conceivably come from SSHRC. Specific examples include:

- **Environmental adaptation.** The arrangement, decoration, and use of working and leisure space to maximize the inhabitant's comfort and performance.
- **Stimulation type and level.** Design and production of equipment and materials to optimize levels of stimulus input and stimulus change, avoiding the adverse effects of boredom, repetitiveness, and sensory restriction.
- **Leadership.** Leadership in space is different from most terrestrial and naval situations. The hierarchy is relatively flat; the leader has few of the accustomed markers and powers. How small-group leadership best functions under such conditions, in multi-year durations.
- **Team morale and compatibility.** Prolonged confinement within a small capsule located within a deadly natural environment puts stress on interpersonal relations. Such stresses may adversely affect cooperation, morale, harmony, and task performance.
- **Cognitive processes.** Cognitive deterioration is a commonly reported experience in isolated, confined environments, including spacecraft. Its specific causes and personality correlates are not known.
- **Terrestrial analogues.** Canada has a large number of isolated communities and jobsites. Knowledge transfer between studies of adaptation to such environments and studies of space psychology would be beneficial to organizations designing and operating both.

4.1.3.4 MITACS

MITACS (formerly Mathematics of Information Technology and Complex Systems) is a non-profit, national research organization that manages and funds research and training programs for undergraduate, graduate students, and postdoctoral fellows in partnership with universities, industry and government in Canada. Most of their programs require matching industry funds but some of the entry programs, for example the Globalink program to bring international undergraduate students to Canada, are wholely funded by MITACS.

4.1.3.5 Canadian Society of Hypertension / Heart and Stroke Foundation

Both of these societies have interests that overlap with those of space health Objective SH-02. In particular, the recent identification of possible vascular endothelial dysfunction occurrence with spaceflight and a possible increased risk for cardiovascular disease in astronauts may provide a research avenue not otherwise available.

4.1.3.6 AGEWELL

Aging Gracefully across Environments using Technology to Support Wellness, Engagement and Long Life (AGE-WELL) was established in 2014 as a National Centre of Excellence to enable Canada to emerge as a global leader in designing technology that optimizes the well-being of older adults. AGE-WELL brings together 30 universities and more than 100 industry and non-profit organizations to address a wide range of complex issues in technology and aging.

Several of AGEWELL's projects involve the use of remote presence technology to monitor patients and managing the well-being of a group with limited resources by empowering that group to act more autonomously and proactively. These technologies would be useful for addressing space health Objective SH-04 and would be useful for the Advanced Crew Medical Systems (ACMS) project.

4.1.3.7 Saskatchewan Pulse Growers

The Pulse Growers have indicated that they would support space health nutritional projects for the price of an endorsement of the project by the CSA.

4.1.4 Backcasting and forecasting the future of human space exploration

Before the research objectives and the associated systems and facilities needed to meet those objectives can be prioritized, it is necessary to have an overview of the direction of the future of space exploration. We will take a backcasting and forecasting perspective to get this overview. With backcasting, we take a look far into the future so that we can think about what kind of technology might be needed, and consider what very early-stage, and long-lead, development is possible today. With forecasting, we take a logical look at what can be realistically built on top of current technology. Before looking at backcasting and forecasting, it is wise to note that we are not the only group to identify and prioritize space health research to identify and eliminate health risks to astronauts; we'll take a brief look at the work already done along these lines by NASA.

Currently the United States' plan for human space exploration is the "flexible path" approach. This path has been proposed as the solution to developing technology in the face of changing political agendas and financial realities. The Global Exploration Roadmap [3] (GER) has Mars as the ultimate goal with the idea that people will one day live and work there. With this goal in mind, a number of reports have been written that assess the health aspects of long-term space flight, and our understanding of the health challenges and countermeasures needed to stay healthy. This CSEW document adds to that literature from a Canadian perspective. One significant point of reference is NASA's Bioastronautics Roadmap [4] which divides space health disciplines into "Cross cutting areas'' which are further divided into "Disciplines". In Table 4-4, a match is made between the Cross cutting areas and the CSEW Space Health Objectives SH-01 to SH-04. The Bioastronautics Roadmap also lists the risk levels for each of three types of mission, ISS (1 year), Lunar (30 days) and Mars (30 months). Those risk levels, determined in 2005 have been substantially revised as new knowledge has become available. Table 4-4 provides the list from the Bioastronautics Roadmap where 45 "risks" are identified.

Table 4-5 Cross Cutting Areas and the CSEW Space Health Objectives

Cross cutting Area	Human Health and Countermeasures (SH-02, SH-03)
Discipline	**Bone Loss**
Risk	1. Accelerated Bone Loss and Fracture Risk 2. Impaired Fracture Healing 3. Injury to Joints and Intervertebral Structures 4. Renal Stone Formation
Discipline	**Cardio-vascular Alterations**
Risk	5. Occurrence of Serious Cardiac Dysrhythmias 6. Diminished Cardiac and Vascular Function
Discipline	**Environmental Health**
Risk	7. Define Acceptable Limits for Contaminants in Air and Water
Discipline	**Immunology & Infection**
Risk	8. Immune Dysfunction, Allergies and Autoimmunity 9. Interaction of Space flight Factors, Infections and Malignancy 10. Alterations in Microbes and Host Interactions
Discipline	**Skeletal Muscle Alterations**
Risk	11. Reduced Muscle Mass, Strength, and Endurance 12. Increased Susceptibility to Muscle Damage
Discipline	**Sensory-Motor Adaptation**
Risk	13. Impaired Sensory-Motor Capability to Perform Operational Tasks During Flight, Entry, and Landing 14. Impaired Sensory-Motor Capability to Perform Operational Tasks After Landing and Throughout Re-Adaptation 15. Motion Sickness

Cross cutting Area	Human Health and Countermeasures (SH-02, SH-03)
Discipline	**Nutrition**
Risk	16. Inadequate Nutrition
Cross cutting Area	**Autonomous Medical Care (SH-03)**
Discipline	**Clinical Capabilities**
Risk	17. Monitoring and Prevention 18. Major Illness and Trauma 19. Pharmacology of Space Medicine Delivery 20. Ambulatory Care 21. Rehabilitation on Mars 22. Medical Informatics, Technologies, and Support Systems 23. Medical Skill Training and Maintenance
Cross cutting Area	**Behavioral Health and Performance (SH-04)**
Discipline	**Behavioral Health & Performance and Space Human Factors (Cognitive)**
Risk	24. Human Performance Failure Due to Poor Psychosocial Adaptation 25. Human Performance Failure Due to Neurobehavioral Problems 26. Mismatch between Crew Cognitive Capabilities and Task Demands 27. Human Performance Failure Due to Sleep Loss and Circadian Rhythm Problems
Cross cutting Area	**Radiation Health (SH-01)**
Discipline	**Radiation**
Risk	28. Carcinogenesis 29. Acute and Late CNS Risks 30. Chronic and Degenerative Tissue Risks 31. Acute Radiation Risks
Cross cutting Area	**Advanced Human Support Technologies (SH-03)**
Discipline	**Advanced Environ-mental Monitoring & Control**
Risk	32. Monitor Air Quality 33. Monitor External Environment 34. Monitor Water Quality 35. Monitor Surfaces, Food, and Soil 36. Provide Integrated Autonomous Control of Life Support Systems
Discipline	**Advanced Food Technology**
Risk	37. Provide Space Suits and Portable Life Support Systems
Discipline	**Advanced Life Support**
Risk	38. Maintain Food Quantity and Quality 39. Maintain Acceptable Atmosphere 40. Maintain Thermal Balance in Habitable Areas 41. Manage Waste 42. Provide and Maintain Bioregenerative Life Support Systems 43. Provide and Recover Potable Water
Discipline	**Space Human Factors Engineering**
Risk	44. Mismatch Between Crew Physical Capabilities and Task Demands 45. Poorly Integrated Ground, Crew, and Automation Functions

The GER provides more up-to-date information on the health risks but, again, new knowledge requires a revision of the perceived risks. The priorities given to space health RQs given in this CSEW document reflect the latest knowledge available to the TT. It will be useful for decision makers to compare past risk assessments with the priorities given by the TT, so a brief review of the GER is given here.

The path to Mars, according to the GER, starts with the ISS that will be used well into the 2020s for research in an essentially zero gravity (or micro gravity) environment. After that, missions that return to deep space travel have the Moon, cis-lunar space, asteroids, the moons of Mars and Mars itself as destinations. The common goals and objectives of the GER are listed here for reference:

- GER-1. Develop Exploration Technologies and Capabilities
- GER-2. Engage the Public in Exploration
- GER-3. Enhance Earth Safety
- GER-4. Extend Human Presence
- GER-5. Perform Science to Enable Human Exploration
- GER-6. Perform Space, Earth, and Applied Science
- GER-7. Search for Life
- GER-8. Stimulate Economic Expansion

More specific to space health are the "Main Human Health and Performance Risks for Exploration" listed in the GER and reproduced in Table 4-5 for reference against the Space Health Science Objectives listed in Section 4.1.1. In Table 4-5, the following colours are used:

- Red (XXX - Unacceptable – NO GO – Mission limiting): A risk with one or more of its attributes (i.e. consequence, likelihood, uncertainty) currently exceeding established human health and performance standards for that mission scenario.
- Yellow (XX - Acceptable – GO – Not mission limiting but increased risk): A risk with all of its attributes (i.e. consequence, likelihood, uncertainty) well understood and characterized, such that they meet existing standards but are not fully controlled, resulting in "acceptance" of a higher risk posture. Lowering the risk posture is important, but the risk is not expected to preclude a mission.
- Green (X - Controlled – GO – Not mission limiting): A risk with all of its attributes (i.e. consequence, likelihood, uncertainty) well understood and characterized, with an accepted mitigation strategy in place to control the risk. It is still helpful to pursue optimized mitigation opportunities such as compact and reliable exercise devices.

Table 4-6 Space Health Risks as listed in the Global Exploration Roadmap

CSEW Space Health Objective	Main Human Health and Performance Risks for Exploration	Mission			
		ISS (6mo)	Lunar (6 mo)	Deep Space (1 yr)	Mars (3 yr)
SH-02	**Musculoskeletal:** Long-term health risk of early onset osteoporosis. Mission risk of reduced muscle strength and aerobic capacity	X	X	XX	XXX
SH-02	**Sensorimotor:** Mission risk of sensory changes/dysfunctions	X	XX	X	XX
SH-02	**Ocular Syndrome:** Mission and long-term health risk of microgravity-induced visual impairment and/or elevated intracranial pressure	XX	XX	XXX	XXX
SH-03	**Nutrition:** Mission risk of behavioral and nutritional health due to inability to provide appropriate quantity, quality and variety of food	X	X	XX	XXX
SH-03	**Autonomous Medical Care:** Mission and long-term health risk due to inability to provide adequate medical care throughout the mission (Includes onboard training, diagnosis, treatment, and presence/absence of onboard physician)	X	XX	XXX	XXX

CSEW Space Health Objective	Main Human Health and Performance Risks for Exploration	Mission			
		ISS (6mo)	Lunar (6 mo)	Deep Space(1 yr)	Mars (3 yr)
SH-04	**Behavioral Health and Performance:** Mission and long-term behavioral health risk	X	XX	XXX	XXX
SH-01	**Radiation:** Long-term risk of carcinogenesis and degenerative tissue disease due to radiation exposure – Largely addressed with ground-based research	X	XX	XXX	XXX
Not addressed	**Toxicity:** Mission risk of exposure to a toxic environment without adequate monitoring, warning systems or understanding of potential toxicity (dust, chemicals, infectious agents)	XX	XX	XXX	XXX
Not addressed	**Autonomous Emergency Response:** Medical risks due to life support system failure and other emergencies (fire, depressurization, toxic atmosphere, etc.), crew rescue scenarios	XX	XX	XXX	XXX
SH-02, SH-03	**Hypogravity:** Long-term risk associated with adaptation during intravehicular activity and extravehicular activity on the Moon, asteroids, Mars (vestibular and performance dysfunctions) and postflight rehabilitation	X	X	XX	XXX

The Objectives and the RQs that address those Objectives in this CSEW document are not meant to be comprehensive in terms of what is needed to complete the missions on the flexible path but, rather, are meant to address Canadian capacity and expertise in the field of space health.

4.1.5 Backcasting: The future beyond Mars

If nature doesn't prune our branch of the evolutionary tree and we move away from Earth then we will evolve (see Figure 4-2). It is likely that colonizing other worlds will allow our evolution to proceed more rapidly and in many different directions than would be possible if we remain on the Earth.

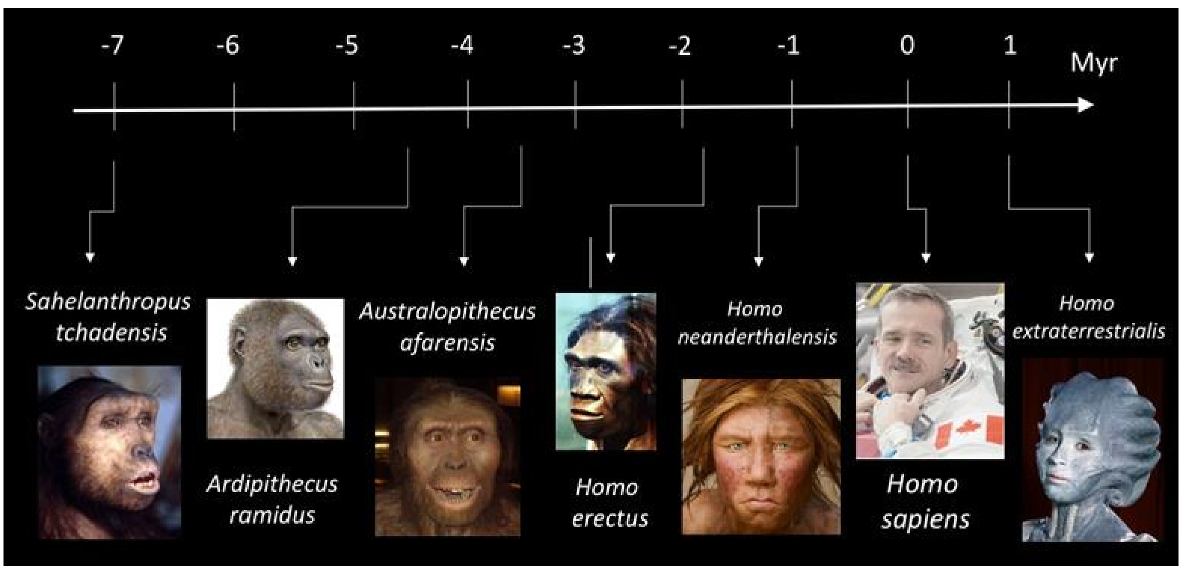
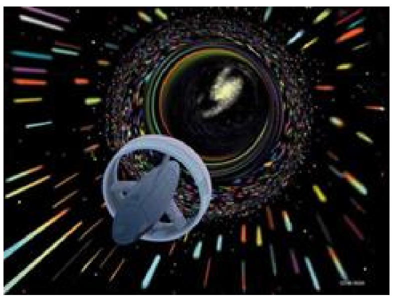


Figure 4-2 We are evolving. Driven by our instinct to explore, our move away from will facilitate our evolution into many diverse new species as the Universe ages.

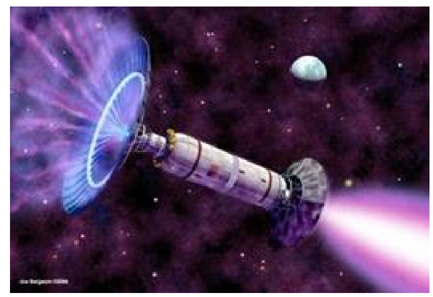
Rocket and other technology will eventually be developed that will allow us to travel to the stars. Such technology might include the Alcubierre warp drive, photon rockets, the controversial em-drive, the high TRL Variable Specific Impulse Magnetoplasma Rocket (VASIMR) or nuclear rockets of various designs (see Figure 4-3). Some of these designs have the promise, within a decade or so, to enable travel from the Earth to the Moon in a matter of hours instead of days or, from the Earth to Mars in a matter of weeks instead of months. The relatively near-term possibility of fast trips to Mars suggests that investing in advanced rocket technology as per objective GER-1, may eliminate the possibility of astronauts needing to spend months living in a zero-gravity environment, with all the challenges addressed in this document.

When we get to the stars, to the exoplanets currently being studied by astronomers, we will have an understanding of climate change to a level where climate change can be engineered. We will have, and need, the capability of transforming a potential exoplanet home into an Earth-like planet suitable for us by terraforming it. Terraforming technology will likely have been developed for Mars long before we set off to settle the exoplanets.

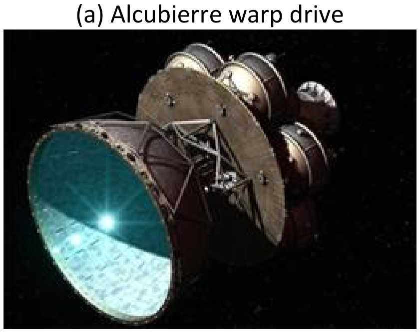


(a) Alcubierre warp drive

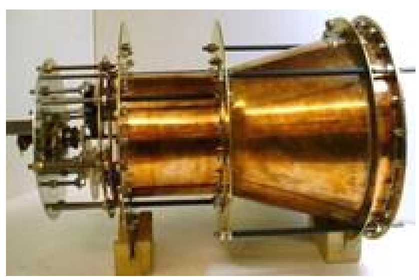
(b) Photon rocket



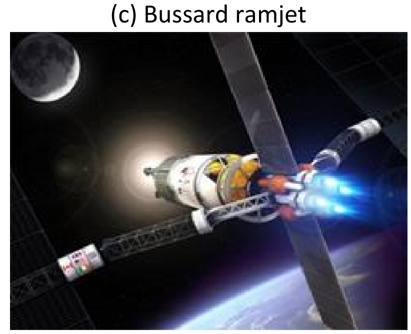
(c) Bussard ramjet



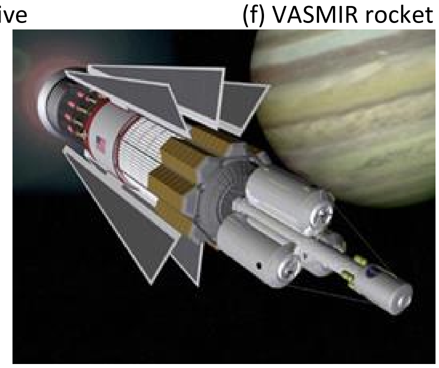
(d) Daedalus pulsed nuclear explosions



(e) Controversial em-drive



(f) VASMIR rocket

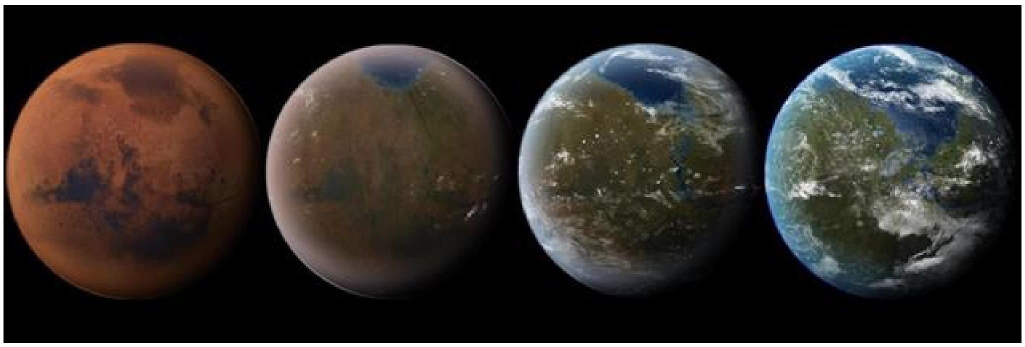


(g) Nuclear rockets first designed and tested in the 1960 (h)

Figure 4-3 There are many ideas for future rocket designs that will get us deep into the solar system and to the stars. Some of these ideas have the potential to make the trip from the Earth to the Moon in hours instead of days and from the Earth to Mars in weeks instead of months.

4.1.6 The Ethics of Colonizing Mars

The ultimate goal of going to Mars is to live there. For Mars to become a "second home" for humanity, it needs to be terraformed – converted using deliberate Martian climate change engineering (see Figure 4-4). Such a change will likely destroy any existing Martian life. We need to consider the ethics of doing that. Perhaps the availability of a second home will outweigh the loss of any native Martian life. Before any terraforming activity, Martian life may be hard to find and exploration by anything other than sterilized robot probes risks contaminating Mars and destroying the hope for answering Objective GER-7 for Mars. On the other hand, some scientists believe that life exists below the surface, and it may only be discovered when human explorers with large drilling machinery are there to do the job.



Mars now → Human settlement → Terraformed Mars

Figure 4-4 To make Mars into a "second home" for people, it will need to be terraformed. Terraforming could take centuries [5]

4.1.7 Forecasting: The Necessity of a Lunar Base

After spending months in a zero-gravity environment, astronauts making the first trip to the Martian surface will need to recover and readapt to the Martian gravity and then live for several months in the 1/3 Martian hypogravity – see Figure 4-5. We currently have no data on the long term effects of living in microgravity, how it affects health and performance. It would be very much easier, and cheaper, to obtain health hypogravity data by living on the Moon instead of Mars. That fact, plus the argument of developing the engineering needed closer to home, plus the fact that we might want to wait and see if there is native Martian life with robot exploration, points toward the technical necessity of developing a lunar base, or lunar village as is currently in ESA's plans for the 2030s (see Figure 4-6). Also, the existence of a lunar base can become the focal point for the development of an extraterrestrial economy. The Moon gives tourists an actual destination, for example, where they could participate in the development of Moon colonies. The Moon will also offer an opportunity to do science, for example the construction of a radio telescope array much larger than the Square Kilometer Array (SKA) now being built in south Africa and Australia, that is not possible to do on Earth or Mars.

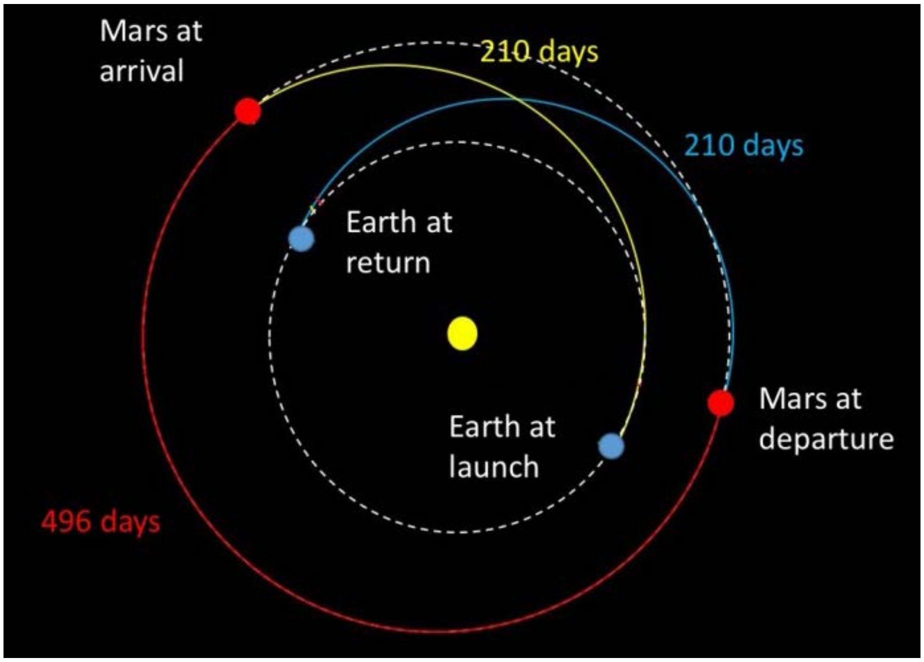
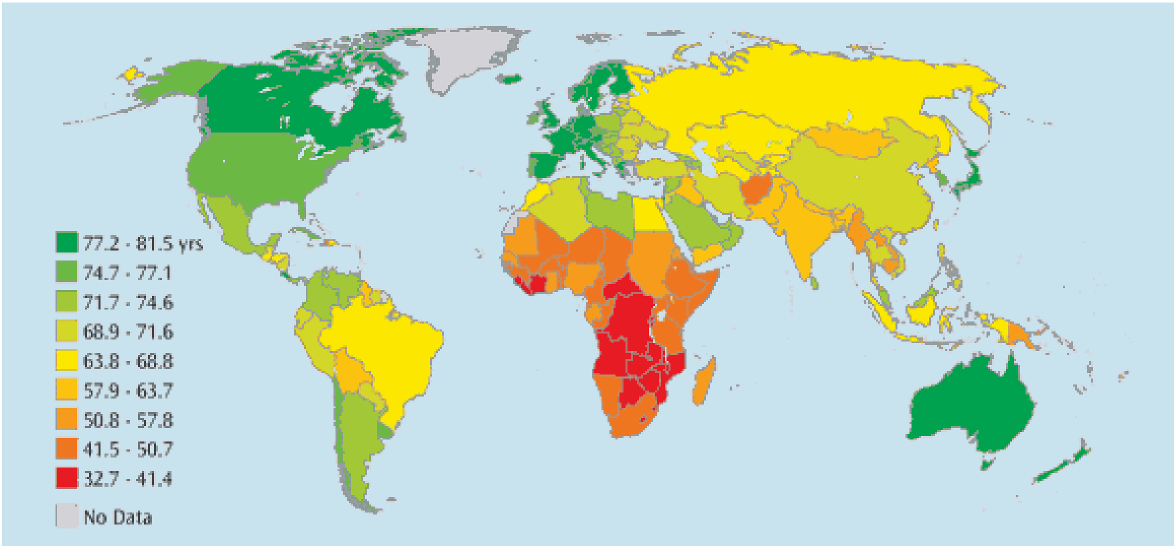


Figure 4-5 Travel to Mars via Hohmann transfer orbits and then landing involves more time in Martian hypogravity than in zero-gravity [6]

Figure 4-6 ESA is planning a Lunar Village for the 2030s. It makes sense, especially from a space health knowledge point of view, to develop our ability to live on the Moon before we attempt to live on Mars

4.1.8 Space health technology is necessary for our survival

Independent of our goal to become a multi-planet species(s), we need to figure out how to keep a potential Earth population of 10 billion people, healthy, happy and fed. We have, to date, managed to stay ahead of the demand for resources [7] and we need to keep doing that. With an accelerating growth in population (Figure 4-7), we need to accelerate our development of technology, of agricultural approaches and health care knowledge. Developing human health technology for space travel provides the necessary motivation to accelerate the critical technology development before we need it so that it is available when we need it.



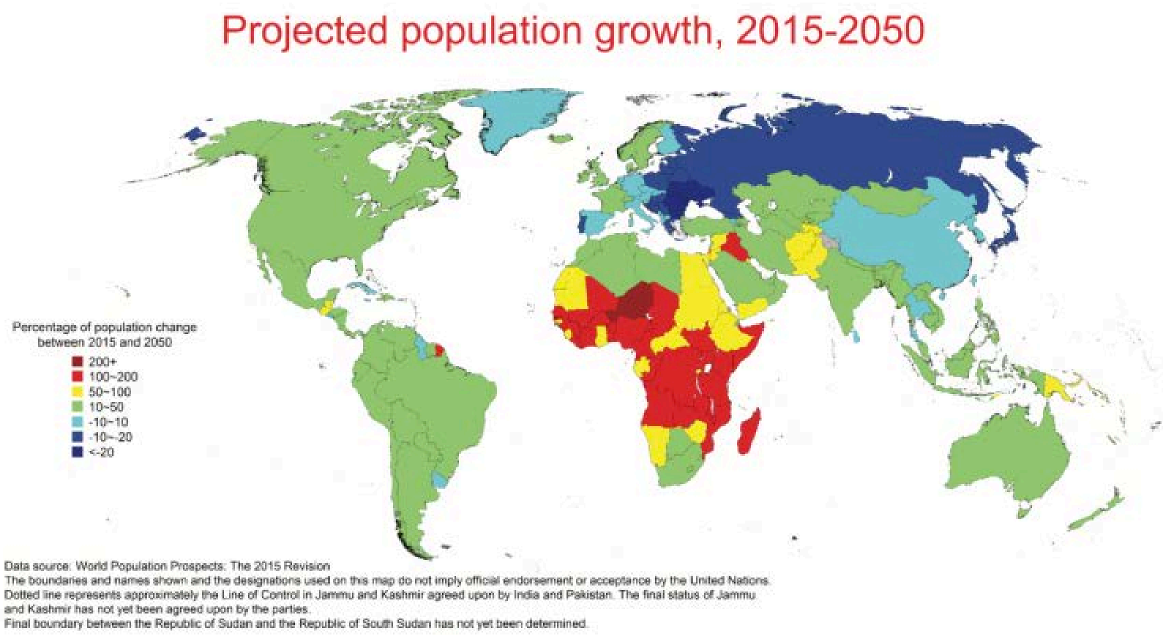


Figure 4-7 Maps taken from the internet that show:
Top: The disparity in human health as quantified by life-expectancy.
Bottom: The projected growth of the human population to approximately 10 billion people in 2050.

Advances in health technology, motivated by following the Global Exploration Roadmap, will be vital for successfully managing an increasing population and ensuring that everyone has a chance to live a healthy life

Finally, we point out that space health research should be an easy-to-sell to the tax-payer, given a well-designed outreach program, because absolutely everything learned has direct application to aging and healthy lifestyles (including the psychology of how not to kill each other). One outstanding example is the research looking for countermeasures to radiation exposure, using food and drugs, where the research looks for ways to prevent cancer from occurring in the first place. This approach is one step ahead of "early detection" and could have wide impact. The impact could be similar to how people rarely have cavities now because of fluoride in drinking water. By working on problems that seem to have no direct connection to health problems that people normally worry about, we open up the door to more serendipitous discovery that can change the overall health of people and the society they live in.

4.2 Space Health Objectives and Research Questions

Four space health science objectives, from the CSEW6 report, were identified by the CSA, in consultation with the TT, as being currently relevant to the CSA. These objectives are given here along with RQs that need to be answered to meet the objectives. Descriptions of the systems, facilities and measure necessary for answering the science questions are also given. The RQs are prioritized following the criteria given in Section 4.1.1.1, and the necessary systems and facilities necessary to answer those RQs are identified. The Space Health Science Objectives are listed in Section 4.1.1.

The numerical priorities, as given here, must be regarded as first approximations. Rationale for the quantification has been given in the preceding sections, but the actual prioritization of one RQ over another is a bit like asking if you'd like to die by heart attack or cancer (quite almost literally). The systems and facilities are prioritized by counting the number of RQs they are associated with. The RQs were formulated by different writers from the TT who work in diverse fields where there may be a large number of small questions to be answered, or there may be a few large questions to answer. While we have tried to make the formulation of questions as uniform as possible, a conscientious decision maker will read some of the details presented in this document as opposed to treating the quantification given here as absolute.

4.2.1 Research Questions

The two-dimensional priority scores for the RQs are given in Table 4-6 and plotted in Figure 4-8.

It is important to note that the RQs have varying levels of granularity, although we tried to minimize that variation so that the questions could be reasonably compared. It is also very important to note that there is a very large amount of interaction and recurring themes between not only the RQs, which frequently are more proposed *research programs* than questions *per se*. For example, the issue of nutrition/food bears on countermeasures for radiation tolerance, cardiovascular protection and even mental well-being, and so aspects of nutrition/food appear across all Objectives.

Table 4-7 List of RQs and their Priority Coordinates and Rank**

	Research Question (RQ) **(Merit, Community / Benefit)*	**(M, C/B)* Score**	**Priority Score**
	Objective SH-01: Radiation		
RQ-01	What is the composition of space radiation?	(11, 5)	12.1
RQ-02	Can we develop foods that protect against radiation?	(11, 5)	12.1
RQ-03	How does space radiation affect the human body?	(10, 4)	10.8
RQ-04	What shielding countermeasures can be implemented to protect astronauts on long-duration missions?	(10, 3)	10.4
RQ-05	What are the individual sensitivities that affect the space radiation risk and how should post mission care be enhanced?	(9, 3)	9.5
RQ-06	What are the behavioural and neurophysiological consequences of radiation exposure?	(8, 3)	8.5
RQ-07	Does space radiation adversely affect the growth of plants?	(8, 3)	8.5
RQ-08	Are computer codes used for radiation protection of astronauts and space assets sufficiently accurate?	(9, 3)	9.5
RQ-09	Does neutron activation of components used in spacecraft increase the radiation risk to humans?	(8, 3)	8.5
RQ-10	What is the impact of the South Atlantic Anomaly on radiation exposure in low-Earth orbit?	(8, 3)	8.5
RQ-11	Are current spacecraft optimally designed for radiological protection?	(9, 3)	9.5
RQ-12	How does solar activity affect the radiation risk to humans?	(8, 3)	8.5
RQ-13	Do solar neutrons contribute significantly to radiation exposure to humans?	(8, 3)	8.5
RQ-14	What should be the protocol for in-situ shielding at a lunar base?	(10, 3)	10.4
RQ-15	What are acceptable radiation dose limits and criteria for deep space exploratory missions?	(8, 3)	8.5
RQ-16	Which radiation transport codes and which input models are most appropriate?	(7, 3)	7.6

	Research Question (RQ) *(Merit, Community / Benefit)*	(M, C/B)* Score	Priority Score
RQ-17	How do we define a worst case solar particle event (SPE)?	(7, 3)	7.6
RQ-18	How do we define a reference mission scenario for low-Earth orbit and deep space?	(7, 3)	7.6
RQ-19	How can radiation transport codes and computer models help address biological effects of radiation?	(8, 4)	8.9
RQ-20	What is the radiation environment at suborbital altitudes?	(8, 3)	8.5
RQ-21	How do high-charge and high-energy particles interact with matter?	(8, 3)	8.5
	Objective SH-02: Physiology		
RQ-22	Find the optimal exercise prescriptions for countering muscle mass and function loss.	(10, 2.75)	10.37
RQ-23	Further study of partial-G environments to prepare for human activity on the Moon and Mars.	(9, 2.75)	9.09
RQ-24	Development of novel countermeasures and protocols to counter muscle mass and function loss.	(10, 2.75)	10.37
RQ-25	Knowledge of the dominant cellular mechanisms underlying spaceflight atrophy to inform the development of pharmaceutical or nutritional adjuncts.	(10, 2.75)	10.37
RQ-26	Integrated investigations of physical health.	(10, 2.75)	10.37
RQ-27	*Exercise and cardiac function:* What devices and exercise routines will simultaneously meet the physiological and psychological demands of exercise training and leisure time activities while being constrained to the dimensions of future exploration platforms?	(9, 5)	10.30
RQ-28	*Cardiac structure and function:* Will there be alterations in cardiac structure and function as assessed by changes in cardiac mass and performance on exercise tests?	(7.5, 5)	9.01
RQ-29	*Vascular structure and function:* Does vascular endothelial dysfunction occur with spaceflight?	(7, 5)	8.60
RQ-30	*Cardiometabolic health:* Can the development of insulin resistance be prevented by exercise and/or nutrition interventions?	(9, 5)	10.30
RQ-31	*Cerebrovascular health:* What factor(s) underlie development of Vision Impairment Intracranial Pressure (VIIP) syndrome?	(9.9, 3.6)	10.53
RQ-32	A better understanding of brain fluid regulation and of the state of the blood-brain or blood-retinal barrier is needed and crucial to better understand the effects of spaceflights on mental and retinal health.	(9.8, 3.6)	10.44
RQ-33	How does the vestibular system respond to zero-g?	(7, 4)	8.06
RQ-34	How much artificial gravity is required to provide reliable orientation cues?	(5, 4)	6.40
RQ-35	Is vulnerability to space-sickness correlated with the state of the vestibular system?	(4, 4)	5.66
RQ-36	What is the relationship between skin input and proprioception/orientation?	(9, 3)	9.49
	Objective SH-03: Integration		
RQ-37	Is it possible to conduct tele-operated surgical and medical treatments from earth, when the interventional suite is located inside the ISS using a master-slave robotic paradigm?	(10.8, 2)	10.98
RQ-38	Can effective point of care diagnosis and medical/surgical treatments be accomplished using remote presence robotic technology at space travel distances?	(11, 4.5)	11.88
RQ-39	Can we exploit biological systems (plants) to incrementally advance life support technologies to produce food, oxygen, recycle fresh water and scrub carbon dioxide while also addressing aspects of human health through remediation (plums, pulses) or mitigating negative effects (radiation shielding)?	(11, 4.2)	11.77
RQ-40	Can we develop food growing technology to the point where we can grow food on the Moon?	(10, 4.2)	10.85
RQ-41	Can pulse-based nutraceuticals and/or probiotics provide effective dietary countermeasures for health problems?	(7.4, 4)	8.41
RQ-42	What psychological characteristics/competencies make individuals most able to function in isolated extreme and/or Moon/Mars analogue environments?	(6.5, 3.5)	7.38
RQ-43	How can knowledge of psychological characteristics/competencies be leveraged to assist in assembling high-functioning, healthy crews who will experience high cohesion, low conflict, and mission success in isolated extreme and/or Moon/Mars analogue environments?	(6.5, 3.5)	7.38

	Research Question (RQ) *(Merit, Community / Benefit)*	(M, C/B)* Score	Priority Score
RQ-44	Develop key medical capabilities essential for human space exploration, in collaboration with international partners.	(10, 4)	10.77
RQ-45	Build robust space medicine capacity in Canada.	(11, 5)	12.08
RQ-46	Integration and translation of past and present life sciences research and operational experience to create individualized crew performance programs for all phases of exploration missions.	(8, 3)	8.54
	Objective SH-04: Psychology		
RQ-47	Understand isolation issues.	(7,2)	7.28
RQ-48	Will the development and use of virtual reality apparatus provide a partial countermeasure for the psychological consequences of isolation?	(5.2, 1.5)	5.41
RQ-49	How will we deal with common social and psychological problems in space and in future planetary colonies?	(5.8, 2.7)	6.40
RQ-50	How can we widen our research and technical innovation beyond problems and countermeasures, to address the enhancement of health, resilience, morale, and task performance above baseline for people who are adequately solving their problems and adjusting to their environment?	(5.5, 2)	5.85
RQ-51	What are the priorities in research that integrates questions deriving from all components of the bio-psycho-social human organism in space?	(8, 2)	8.25
RQ-52	Can a protocol be developed for collecting and amassing a meaningful set of data on team functioning in Canadian analogue environments?	(7,2)	7.28
	** The priority rank is the Euclidean distance of the priority coordinates from the origin.		

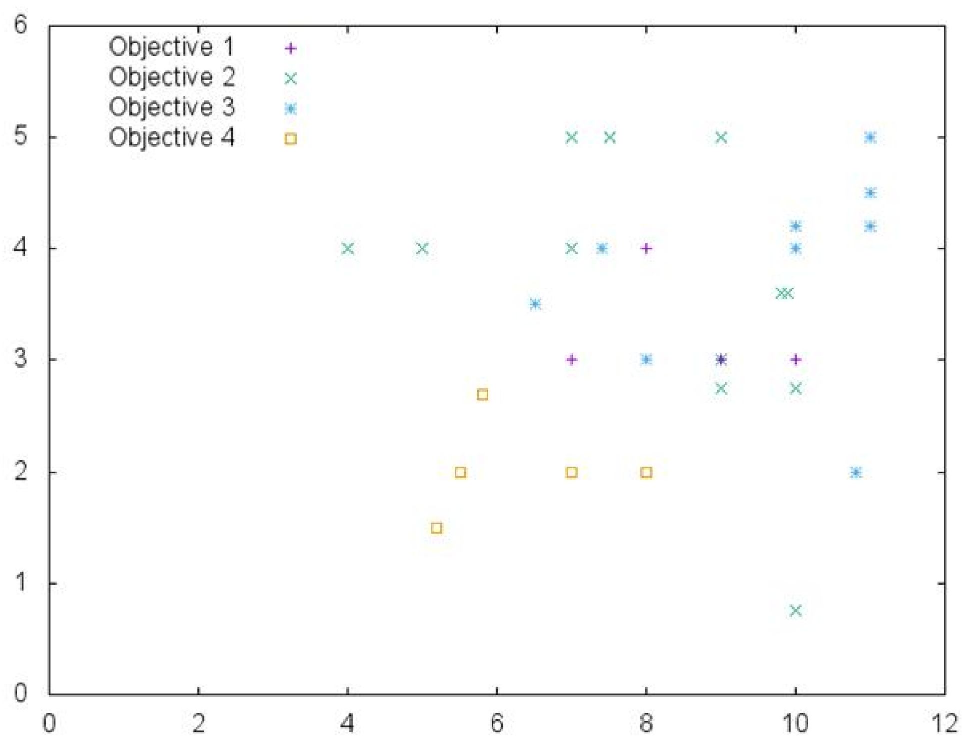


Figure 4-8 Research Question Priorities

A summary description of the research questions by Objective follows.

Detailed rationale for ranking is provided in a longer version of the report, available from the CSA or the TT chair.

4.2.2 SH-01: To better understand the risks to living organisms of radiation exposure beyond low-Earth orbit and develop effective countermeasures

> *"Space radiation is a big concern for astronauts ... [neutrons] can travel deep inside the living tissue and these unstable particles have the potential to damage or mutate DNA, which can cause cataracts or even cancer."*
>
> *– Chris Hadfield*

Travel beyond LEO involves exposure to radiation that has the potential to cause cancer and non-cancer diseases, which may be potentially deadly. The radiation fields found at some of the more interesting destinations in the solar system, such as Jupiter's moon Europa with its underground sea, are dangerous even for robots. In the near future, humans will return to the Moon and make long journeys into interplanetary space, targeted at destinations such as asteroids, the Moon, and Mars. These journeys may expose astronauts to dangerous levels of radiation if they are not appropriately protected. Radiation monitoring and protection is therefore required for these missions, along with greater understanding of what happens to the human body after long-term exposure to the space radiation environment. To gain this understanding, ongoing experiments are conducted on the ISS.

The CSA has consistently identified radiation prediction, monitoring, and protection technologies as a key Signature Technology for the Canadian space exploration program since the concept of Signature Technologies was introduced several years ago. Mitigation of space radiation continues to be listed as a CSA Signature Technology in the most recent CSA documentation. According to the CSA definition:

> *…..a CSA Space Exploration Signature Technology is a Canadian product or product line for which Canada is, or has the potential to become, a world leader and that can be used for multiple government-driven space missions over an extended period of time.*

(1) RQ-01: What is the composition of space radiation?

Although measurements of radiation in space, particularly in LEO, have been conducted for many years, the composition of space radiation, i.e., particle types, energy distributions, and relative abundance, is not well quantified. This is particularly true for neutrons. Better data will allow improved assessment of the health risk to astronauts on long-duration missions. An instrument such as the Canadian High-Energy Neutron Spectrometry System II (CHENSS-II), which can accurately measure the neutron energy spectrum to high energies and provide information on the charged-particle components of space radiation, is essential to gathering this knowledge. The CHENSS-II would initially be used on the ISS but could later be reconfigured for Moon and Mars missions. The measurements would be supported by modelling of the radiation field in deep space.

The development of the CHENSS-II, with associated signal processing and spectral unfolding, will simultaneously push Canada to the forefront of space-based radiation dosimetry and enable major advancements in a number of Earth applications that provide benefits to Canadian society, and which align with Government priorities. Terrestrial applications span a wide range of domains including: medical applications in cancer therapy; radiation protection of military and civilian aircrew personnel; defense and public security applications in nuclear and explosive threat detection; and advancement of fundamental nuclear science.

(2) RQ-02: Can we develop foods that protect against radiation?

"Radiation therapy cancer patients have a major interest in nutritional protection from radiation, however the recommendations are not evidence based"
– Catherine Field, Professor of Nutrition, Department of Agricultural, Food and Nutritional Science

Development of nutritional countermeasures is an area with terrestrial medical applications and a clear possibility for leveraging health funding and research. The work on space compatible fruit trees (performed at the U. of Guelph) is related to this, as a practical way to make healthy foods available in space. Pharmaceutical radioprotectants might also be considered as a long-term countermeasure; however, more research in this area is also needed.

(3) RQ-03: How does space radiation affect the human body?

While considerable work has been performed to investigate the effects of radiation on the human body, further investigations are required to fully understand the risk to astronauts, including non-cancer risks such as cardiovascular disease. Radiobiological experiments using animals and cell lines, which could be performed using facilities at Canadian Nuclear Laboratories (CNL) and elsewhere, would improve our biological understanding. Radiation measurements with animals and cell cultures on satellites (beyond LEO) have also been discussed with the CSA and should be performed. Meanwhile, further experiments on the ISS, particularly the continued development of the DNA dosimeter, the planned experiments using bubble detectors with an anthropomorphic phantom, and the Health Canada astronaut biodosimetry program, will continue to make great contributions to our biological understanding of radiation. Improved understanding of the biological impact will have terrestrial benefits in all areas where humans are exposed to radiation in their daily lives.

(4) RQ-04: What shielding countermeasures can be implemented to protect astronauts on long-duration missions?

Even if space radiation and its effects on humans were well understood, it is inevitable that astronauts will encounter significant radiation during exploration missions to the Moon and Mars. Countermeasures are therefore required as part of the planning process for these missions. As discussed above, shielding of space radiation is complicated and more research, including better knowledge of radiation fluxes, is required to develop optimized shielding for travel in deep space. For exploration missions, development of a space-radiation storm shelter and real-time radiation alert systems have the potential to reduce crew exposure risk from Solar Particle Events (SPEs).

(5) RQ-05: What are the individual sensitivities that affect the space radiation risk and how should post mission care be enhanced?

Evidence suggests that individuals may be affected differently by radiation, and further research should be performed to understand individual sensitivities. Post mission care for astronauts should be improved with a particular focus on those health aspects that can be affected by exposure to the space radiation environment.

(6) RQ-06: What are the behavioural and neurophysiological consequences of radiation exposure?

The behavioural and neurophysiological consequences of radiation exposure have been reported. The behavioral effects of ionizing radiation (such as from protons and high-Z particles) in space are being actively explored but more research in this area is required.

(7) RQ-07: Does space radiation adversely affect the growth of plants?

The ability of humans to grow their own food in space is vital to future space exploration, and some work has been performed in this area by Canadian groups including the U. of Guelph. Radiation in space may be detrimental to the growth of plant-based food and its effects should be investigated. Experiments could be conducted on the ground and on the ISS to improve our knowledge in this area.

(8) RQ-08: Are computer codes used for radiation protection of astronauts and space assets sufficiently accurate?

A number of computer codes are currently used to calculate quantities related to radiological protection of humans and assets in space, and for planning space missions. These codes are based on experimental data where possible, but data are not always adequate. Neutrons are mainly secondary products of interactions of charged-particle components of cosmic rays. Uncertainties in our knowledge of cosmic rays will be strongly manifested in the neutron spectrum. Unfortunately, the high-energy neutron spectrum in space is not well known, and is a key component of the radiation protection framework. Measurements of the neutron spectrum in space, using an instrument such as the CHENSS-II, are therefore key to benchmarking that computer codes in common use provide an accurate assessment of the radiation risk.

(9) RQ-09: Does neutron activation of components used in spacecraft increase the radiation risk to humans?

Components used for the exterior and interior of spacecraft can become radioactive following exposure to space radiation, in particular neutrons. An accurate measurement of the neutron spectrum associated with these components will provide important information to be used in assessing whether this activation significantly increases the radiation risk to humans inside the spacecraft.

(10) RQ-10: What is the impact of the South Atlantic Anomaly on radiation exposure in low-Earth orbit?

For missions in LEO, it is well known that a large fraction of the radiation dose to astronauts is received while traversing the South Atlantic Anomaly (SAA). However, the particle composition of the SAA is not well quantified, and the influence of the SAA on the neutron radiation field is not well understood. Accurate measurements of the neutron energy spectrum and neutron exposure rate, tagged with precise location and time stamps, are required to investigate this question in more detail. This tagged information is not available from simple bubble detectors, which provide neutron dose equivalent and limited spectral information averaged over long measurements (days or weeks, for example). However, the data required will be provided by the CHENSS-II, which has the capability of telemetering location- and time-stamped data to Earth in near real time.

(11) RQ-11: Are current spacecraft optimally designed for radiological protection?

The design of a spacecraft includes many aspects, typically dominated by size, weight, and power considerations. Protection of the crew from radiation is a factor in spacecraft design that does not always have the highest priority. Data on charged particles and high-energy neutrons are required to inform spacecraft design, so that materials can be optimally chosen to reduce the radiation exposure to the crew. In particular, it may be possible to improve shielding around key areas of the spacecraft, including the astronaut sleeping quarters.

(12) RQ-12: How does solar activity affect the radiation risk to humans?

It has been observed that the neutron dose equivalent measured by bubble detectors on the ISS is not strongly influenced by quantities such as solar activity. This seems to contradict results from other instruments used on the ISS that measure the total radiation dose from all particles. Accurate measurements of the high-energy neutron spectrum, tagged with location and time, are required to assess the impact of solar activity.

(13) RQ-13: Do solar neutrons contribute significantly to radiation exposure to humans?

Solar neutrons, i.e. neutrons emitted by the Sun, may contribute to the radiation exposure received by astronauts outside of LEO. In order to investigate this question, measurements have been suggested on the Orion test flights around the Moon, using a payload based on the CHENSS-II. The goal of these experiments is to measure the neutron dose on orbit around the Moon, and to correlate these measurements with time and location. Correlation of the neutron dose with the position of the Moon, Earth, and the Sun is of particular interest for determining the relative contributions of various sources of neutrons. The production of neutrons on orbit around the Moon is due to processes that are considerably different from those that create neutrons in LEO, for example, inside the ISS. The much lower mass of Orion, compared to the ISS, will reduce the impact of the spacecraft itself on the measured neutron dose, therefore enhancing the detection sensitivity for neutrons from external sources, including neutrons coming directly from the Sun.

(14) RQ-14: What should be the protocol for in-situ shielding at a lunar base?

When humans return to the Moon and set up a lunar base, radiological protection of humans will become a priority. Transportation of heavy radiation shielding will likely be impossible, so in-situ shielding will need to be set up. Radiological data are required to determine the best strategies for shielding, including temporary shielding in response to a radiation alert. Measurements of neutrons and charged particles are particularly important to this effort.

(15) RQ-15: What are acceptable radiation dose limits and criteria for deep space exploratory missions?

Current radiation dose limits for crew are intended for missions in LEO, such as aboard the ISS, where the majority of the dose received is from Galactic Cosmic Radiation (GCR) and trapped radiation. In LEO, the expected radiation dose that crew may receive for a given mission length is generally well understood; methods for predicting the radiation dose have even been developed. For long-duration, exploratory missions in deep space, however, these dose limits may be quickly exceeded. In deep space, GCR and SPEs represent the major sources of radiation exposure. To develop radiation dose limit criteria, models must be developed to predict and understand the expected radiation dose that crew may receive from GCR and SPEs. This must also be supported with an understanding of the health effects of space radiation, including acceptable risks to human health. Alternative methods of assessing health risks should also be considered; the concept of radiation dose may not be the most appropriate quantity for biological detriment.

(16) RQ-16: Which radiation transport codes and which input models are most appropriate?

In the published literature, radiation transport codes are routinely used to model the expected radiation dose that crew may receive for a variety of mission scenarios, from LEO to deep space. Each transport code relies on the use of inputs (i.e. models) for describing the space radiation environment in LEO and in deep space. For instance, there are several models that describe GCR, trapped radiation, and SPEs. Spacecraft design and shielding distributions are also typically approximated using simplifying assumptions. Moreover, models are also used to define radiation qualities and for approximating human anatomy. The choice of radiation transport code and input models, however, can significantly impact the estimated radiation dose. This can have significant impact on mission design scenarios. Unfortunately, there is no consensus among the scientific community on which models, and which radiation transport codes, are most appropriate. Is there a mechanism by which reference models and tools can be defined to permit uniformity across the space exploration community?

(17) RQ-17: How do we define a worst case solar particle event?

SPEs represent a radiation risk to crew in LEO and in deep space. Significant effort is being devoted to modelling and predicting the onset of SPEs and several mechanisms have been developed to model the particle and energy distributions of such events. Presently, however, future events remain difficult to predict and a physical understanding of the energy distributions remains poor. In preparing for future deep space exploratory missions, however, assumptions must be made of the worst case scenario SPE. This choice will bound mission parameters including radiation dose limits, spacecraft design, and mission timelines.

(18) RQ-18: How do we define a reference mission scenario for low-Earth orbit and deep space?

Reference mission scenarios must be developed for any mission to LEO and beyond. Among the many mission elements that must be defined are the mission timeline (i.e. when to travel?), mission duration, mission activities (e.g. number of Extra Vehicular Activities (EVAs)), spacecraft design, shelter design, choice of environmental models, radiation protection and monitoring techniques, proper nutrition, health mitigation techniques, and many more. How can we define and decide on the necessary elements for a reference mission scenario? What should Canada's reference mission scenario be?

(19) RQ-19: How can radiation transport codes and computer models help address biological effects of radiation?

Radiation transport codes are typically used in understanding radiation interactions with matter and for assessing quantities such as flux and dose. Recent efforts, however, have begun to focus on developing radiation transport codes that describe the biological damage that radiation interactions can cause to biological tissue. Codes such as Geant4-DNA, for instance, are being developed to describe the interaction of radiation at a DNA scale. The use of such codes should be expanded and developed to help address the physical and biological influences in concert, in order to improve our understanding of the radiation health risks associated with space travel. As noted above, the codes and models require experimental data, including data relating radiation interactions with biological detriment.

(20) RQ-20: What is the radiation environment at suborbital altitudes?

The space radiation environment at suborbital altitudes, in the region of 50 to 200 km altitude, remains poorly characterized. This radiation environment is complicated by many external influences including, most notably, the interaction of cosmic radiation with Earth's atmosphere and production of secondary particle showers. With the advent of space tourism, where vessels are expected to reach suborbital altitudes, increased understanding of the radiation environment will be necessary to help inform radiation protection guidelines. An understanding of this environment must be supported using modelling and experimental techniques.

(21) RQ-21: How do high-charge and high-energy particles interact with matter?

Space radiation is comprised of high energy neutrons, protons, alpha particles, and heavier nuclei including a multitude of exotic particle types. At these high energies, it is essential to account for the production of secondary radiation scatter and fragmentation effects. This secondary particle production contributes to the dose that crew will receive and, significantly, will also have an impact on the health risks that crew will incur from exposure. Currently, these biological effects are typically quantified using operational and protection quantities such as dose equivalent, effective dose equivalent, and gray equivalent. Our understanding of the interaction of high-charge and high-energy radiation with matter, and the calculation of these biological weighted dose quantities, relies on a combination of models, experimentally developed cross-section databases, and radiobiological studies. In order to improve our understanding of the risks of radiation exposure, effort should be focused on improving high-energy physics models, validating these models using experimental means, and developing improved fluence-to-dose conversion factors that better quantify the radiation dose and health risks to crew.

4.2.3 SH-02: To better understand biological and physiological changes that occur in reduced gravity environments and to develop effective countermeasures

We need to understand and mitigate bone and muscle mass (up to 10 per cent of an astronaut's bone mass can be lost in a six-month mission). We need to understand and mitigate cardiovascular deterioration including reduced physical fitness, increased arterial stiffness, vascular endothelial dysfunction with risk for cardiovascular disease, and potential complications of cardiometabolic adaptations related to increased insulin resistance. Topics covered under this objective include, in addition to bone, muscle and cardiovascular studies, studies of the neurological system, especially as it affects balance and perception.

4.2.3.1 Neuromuscular health risks of space environments / Deterioration in bone structure and strength in microgravity and countermeasures

(22) RQ-22: Find the optimal exercise prescriptions for countering muscle mass and function loss and determine:

- Whether sex differences influence unloading responses to acute and chronic exercise
- Safe and efficacious periodization of high-intensity exercises for long-duration spaceflight to conserve both time and resources
- Maximum duration of cessation of exercise (equipment failures, interruptions to routine) before mission is at risk
- Risks and benefits of balance training in a microgravity environment; does it have a negative or positive effect on terrestrial ambulation?

(23) RQ-23: Further study of partial-G environments to prepare for human activity on the Moon and Mars to better understand:

- Injury risks of partial-G loading on muscle, joints and bones after long-duration unloading
- Optimal exercise prescriptions for countering muscle mass and function loss in partial-G
- Fitness requirements for safely achieving anticipated mission tasks

(24) RQ-24: Development of novel countermeasures and protocols to counter muscle mass and function loss, including:

- Optimizing mission-specific hardware requirements (i.e. exercise hardware, artificial gravity)
- Design of comfortable human-to-hardware interfaces for exercise countermeasures intended for long-duration missions and future mission-specific needs
- Experimentation and validation of new protocols and hardware in a bed rest setting prior to validation in a spaceflight setting

(25) RQ-25: Knowledge of the dominant cellular mechanisms underlying spaceflight atrophy to inform the development of pharmaceutical or nutritional adjuncts to exercise including:

- Improved understanding of the signaling pathways for protein synthesis and degradation
- Determine the risk of skeletal muscle insulin resistance in long-duration spaceflight
- Assess potential for improved exercise outcomes via vitamin D, protein/amino acid intake and/or phosphocreatine augmentation

(26) RQ-26: Integrated investigations of physical health including:

- Neuromuscular and tendinous responses to spaceflight and countermeasures
- Neuromuscular, skeletal and cardiovascular interactions in spaceflight deconditioning and potential countermeasures

(27) RQ-27: ***Exercise and cardiac function:***

- What devices and exercise routines will simultaneously meet the physiological and psychological demands of exercise training and leisure time activities while being constrained to the dimensions of future exploration platforms?

(28) RQ-28: ***Cardiac structure and function:***

- Will there be alterations in cardiac structure and function as assessed by changes in cardiac mass and performance on exercise tests?
- And, what is the impact of these changes on ability to complete expected mission tasks and maintain crew health?

(29) RQ-29: Vascular structure and function:

- Does vascular endothelial dysfunction occur with spaceflight and does this increase the risk for cardiovascular disease?
- Does the endothelial dysfunction compound with the structural changes identified in ISS missions?
    - Recent evidence from CSA-funded studies on ISS indicates structural changes in the large elastic arteries of the body with thicker and stiffer walls. Current research is continuing to explore the magnitude of this physiological change and obtaining the first data on the post-flight recovery process.
- The questions remain:
    - What are the underlying causes of these changes?
    - What is the post-flight time course of recovery?
    - Are there long-term health consequences of the changes in vascular structure and function?

(30) RQ-30: Cardiometabolic health:

- Can the development of insulin resistance be prevented by exercise and/or nutrition interventions?
- What are the consequences of insulin resistance on cardiovascular health?

It is appropriate to consider future research questions related to astronaut health during long-duration, space exploration missions, at least in part on the NASA Human Research Roadmap. However, it should also be recognized that several recently identified potential risks, some identified by CSA-funded research, had not been specifically indicated in the list of above research questions.

4.2.3.2 Ocular changes and countermeasures

Evidence indicates that ocular changes occur in a majority of humans exposed to microgravity for prolonged durations. Careful examination reveals optic disc edema, globe flattening, choroidal folds, optic nerve sheath distension, and retinal changes. These anatomical changes manifest as visual acuity shifts of varying severity and/or visual field defects. Although these changes have been described in astronauts for several decades of human spaceflight, original anecdotal accounts did not raise sufficient concern in light of their reversibility and limited impact. These vision changes, however, have been recently found to be more common than previously anticipated, and may represent a significant health concern that could jeopardize the future of human space exploration. Given the urgency and severity of this syndrome, in addition to the fascinating Canadian connections, further contributions towards pursuing ongoing research in this area should be supported.

(31) RQ-31: ***Cerebrovascular health:***

- What factor(s) underlie development of Vision Impairment Intracranial Pressure (VIIP) syndrome?

(32) RQ-32:

- A better understanding of brain fluid regulation and of the state of the blood-brain or blood-retinal barrier is needed and crucial, to better understand the effects of spaceflights on mental and retinal health.
- If there is the possibility of using MRI in flight with gadolinium as a contrast agent, then that would answer many questions?
- There are also serum serum biomarkers of the blood-brain-barrier integrity, such as circulating tight junction proteins: claudin5, occludin and ZO-1.

4.2.3.3 The Vestibular System and Spatial Perception

Going into space is a very disorienting experience. Gravity provides a critical reference for much of our sensory experience, and lack of gravity removes that reference direction with both direct and indirect consequences. The vestibular system of the inner ear responds to both angular and linear accelerations. Gravity is equivalent to a linear acceleration and so the vestibular system normally provides a signal concerning its direction. Vertical head movement is normally associated with both dynamic pitch accelerations (picked up by the canals of the vestibular system) and a change in the direction of gravity (picked up by the otolith part of the vestibular system). In microgravity these two signals are no longer paired in the expected way and a sensory mismatch is registered between two parts of the same end organ. Static orientation is provided by multisensory cues. Vision provides information about the position of the ceiling and floor, and this is matched to vestibular and somatosensory cues to provide an ongoing estimate of the direction of up. Once physical cues to orientation are removed orientation becomes ambiguous. The lack of orientation cues also makes navigation harder. In addition to these direct effects of changes in gravity, it is now becoming clear that the vestibular system is also involved in many aspects of cognition. Removal of the gravity reference system may thus have far-reaching consequences that are presently unsuspected. Exposure to microgravity thus has multiple effects on spatial perception, which are disorienting under both static and dynamic conditions and which are often associated with sickness and nausea. It is important to understand these consequences and develop countermeasures to them.

(33) RQ-33: How does the vestibular system respond to zero-g?

This question includes the following detailed research questions.

- Is tracking of objects (with hands or eyes) affected by zero gravity?
- Are self-motion evoked eye movements (e.g. the vestibulo-ocular reflex) affected?

General issues of navigation in 3D (accuracy, disorientation, mapping).

- Can object locations (defined by vision, sound or touch) relative to a person be properly updated as a person moves (rotates and translates) freely in 3D?

The vestibular system is involved in maintaining our perception of self.

- Is the perception of self-affected in space?
- How accurately does an astronaut know the arrangement and lengths of their arms and legs while floating in space?
- Are astronauts more or less vulnerable to the rubber hand illusion in space (where people can incorporate external objects into their perception of themselves as a result of seeing the object being touched and feeling a synchronized touch)?

- Are sensory thresholds (both for detection and discrimination) affected by zero-g (vision, sound, smell, taste, touch, self-motion - each of which has multiple aspects)?

(34) RQ-34: How much artificial gravity is required to provide reliable orientation cues?

(35) RQ-35: Is vulnerability to space-sickness correlated with the state of the vestibular system?

4.2.3.4 Skin

Skin information from the bottom and top of the feet, is becoming more recognized as a contributor to balance and locomotion. Four unique receptors in the skin provide information on slip, stretch, vibration and timing of contact forces. The ability of the skin to translate information from the environment is key to navigation and stability. Additional to this, skin can be used to enhance body awareness. Stretch of the skin across the back, arm or hand can provide essential information regarding joint position and orientation. We need to better understand the link between skin input and proprioception/orientation.

- How is skin information being used aboard the ISS and can we leverage this input to facilitate orientation cues, body angle cues?

We need to also work to better understand the relationship between skin input to compensate for reduced vestibular acceleration/orientation cues. Work done during the project Hypersole, provided information to support a compensation for vestibular deficits through enhanced skin feedback.

This research [1] showed a link between increased weighting of skin input from the foot sole and decreased vestibular function upon return (following short duration).

- Can we help mitigate vestibular challenges (on orbit and upon return) by providing cutaneous input?

Some more specific questions include:

- Can cutaneous cues/vibration facilitate orientation?
- Both in space and upon return to earth?
- What type of skin input would provide the most comprehensive feedback?
- Vibration? Skin stretch? Enhanced clothing?

- Can intermittent cutaneous input to the feet mitigate balance issues upon return to Earth, both from a sensory perspective and to reduce muscle atrophy?

  Research has shown direct links from skin on the foot sole to activate motor neurons of the upper and lower limb. Additional evidence in support of skin input to mitigate muscle atrophy is based on the use of Russian roman sandals during flight.

  - Can we continue this idea over prolonged periods in long duration flight?
  - Why aren't these being used now?

Summarizing these questions:

(36) RQ-36: What is the relationship between skin input and proprioception / orientation and can countermeasures be based on that relationship?

4.2.4 SH-03: To develop a more integrated understanding of the biological and physiological effects of the space environment and develop integrated countermeasures

As our understanding of the effect of living in space on individual body systems increases we will need to understand how the various systems interact. Beyond the task of understanding how the body reacts to space flight, we will need to have the technology available to keep astronauts alive and healthy. There will be a need to assess general astronaut health, and manage and care for ill and injured astronauts. For example, we can assess and obtain information useful for mitigating tissue radiation damage by monitoring changes in telomere length and related astronaut vascular health using Vascular Echo. We could assess and obtain information useful for mitigating ocular pressure and other health problems caused by global body fluid shift using MRI, based on outcomes of current hypothesis-driven studies that explore the effects of global body fluid shifts and other factors. People need to eat and, just as on Earth, they should eat healthily. Nutrition (including immune system effects), in-situ food production and nutraceuticals (e.g. a cocktail of antioxidants for reducing radiation effects) will all be very important for the successful human exploration and colonization of space and other planets.

4.2.4.1 Surgical Systems

Canada has significant and in some cases world leading experience in tele-operated robotic surgical systems. Robotic surgery can provide advantages over traditional approaches by enhancing the dexterity and precision of tool manipulation and provides a framework to integrate advanced medical imaging such as ultrasound, MRI or Computed Tomography (CT) data, to minimize the invasiveness of surgery. The combination of capabilities can also be thought of as reducing the skill required by the user to perform a procedure, which is a potentially valuable feature.

The inclusion of a robotic surgical system in a space mission context would need to be the subject of a more complete system analysis of the medical conditions, to be considered in a mission scenario; the spectrum of possible strategies to address the conditions; and a cost/benefit analysis considering the highly constrained resources available for a long-duration human spaceflight mission. Most current robotic surgical systems are too complex, bulky and heavy to be practical for a space habitat. Augmenting the local crew capability with technologies and approaches related to robotic surgical systems might be the path to providing a value-added solution that merits consideration.

The development of this platform will represent a significant Canadian innovation towards improving the health of astronauts and space travellers.

(37) RQ-37: Is it possible to conduct tele-operated surgical and medical treatments from earth, when the interventional suite is located inside the ISS using a master-slave robotic paradigm?

(38) RQ-38: Can effective point of care diagnosis and medical/surgical treatments be accomplished using remote presence robotic technology at space travel distances?

4.2.4.2 Spacecraft Exercise Systems

The ISS is currently equipped with exercise devices enabling training of the cardiorespiratory and musculoskeletal systems. The devices onboard ISS include: The US supplied devices - treadmill with loading harness (T2, Combined Operational Load Bearing External Resistance Treadmill (COLBERT)); cycle ergometer with vibration isolation and stabilization (CEVIS); and, advanced resistance exercise device (ARED). The Russian supplied devices – treadmill (Б Д-2), cycle ergometer (В Б-3), a force loader (Н С)-1) and resistance bands. In addition, the Russians use static loading with the Penguin-3 suit which is worn for 6-8 h/day loading up to 50% of the crew member’s weight on the ground, and electrical muscle stimulation (Tonus-3). The Muscle Atrophy Research and Resistance Exercise System (MARES) is not currently used for exercise training.

4.2.4.2.1 Implementation of exercise programs and future directions

A history of the evolution and application of countermeasures in the Russian space program was described by Yarmanova and Kozlovskaya. The devices that have been employed by the Russians on ISS have included: U.S. Treadmill with Vibration Isolation and Stabilization System (TVIS), cycle ergometer (В Б -3), a set of resistance bands, a postural muscle loading suit (Penguin-3), electrical stimulator (Tonus-3), compression high cuff s (Braslet-M), a Lower Body Negative Pressure (LBNP) suit (Chibis), a lower body g-loading suit (Kentavr).

A key element of the Russian program has been the periodization, which refers to the cycling of exercise and other countermeasure type and intensity depending on the phase of the mission. They define five stages that define the:

(1) initial phase (flight days 1-10),

(2) condition stabilization phase,

(3) pre-EVA,

(4) final phase (final 30 days of flight), and

(5) descent phase and the first few days of re-adaptation.

Specific countermeasures are required in each phase. However, the longest phase of stabilization also requires planning of micro-cycles in which the type and intensity of exercise is varied. The first day of a micro-cycle is aimed at maintaining speed and load-bearing endurance through treadmill running. The second day focuses on load-bearing endurance training also on the treadmill. The third day includes slow and medium speed running or cycling. The fourth day is active rest. All phases can include the static loading by the postural loading suit. Monthly evaluation of fitness is conducted in a treadmill test with progressive increases in intensity. Also, prior to EVA, Russian cosmonauts undergo a fitness evaluation with leg and arm cycling.

4.2.4.2.2 Food aspect of Environmental Control and Life Support Systems

Environmental Control and Life Support Systems (ECLSS), also known as Advanced Life Support (ALS) systems, provide the conditions necessary to sustain human life. They are divided into two types: Physico-chemical Life Support Systems (PCLSS) and Bio-regenerative Life Support Systems (BLSS). At present, only PCLSSs have been used for spaceflight; however, significant advances in BLSSs continue to demonstrate promising advantages and increasing Technology Readiness Levels (TRLs). Future long-duration, long-distance human spaceflight will likely depend on both physico-chemical and bio-regenerative capabilities. The required functional capabilities of an ECLSS include those listed in Table 4-8.

Table 4-8: Required Functional Capabilities of an ECLSS

System	Functional Capabilities
Atmospheric	• Air Revitalization including gas storage, CO2 removal/reduction, oxygen and nitrogen generation, Trace Contaminant Control (TCC) • Atmospheric Monitoring and Control: • Temperature, humidity, contaminant removal, fire detection and suppression • Dust mitigation
Water Management	• Urine Recovery • Hygiene recovery and potable processing • Water recovery from condensate • Water quality monitoring • Food management and processing
Waste Management	• Feces collection and storage • Solid waste treatment
Radiation protection	

(39) RQ-39: Can we exploit biological systems (plants) to incrementally advance life support technologies to produce food, oxygen, recycle fresh water and scrub carbon dioxide, while also addressing aspects of human health through remediation (plums, pulses) or mitigating negative effects (radiation shielding)?

More detailed questions implied by RQ-39 include two key questions:

- What methods can we use to produce food (and oxygen and water) more efficiently (and nutritiously and reliably) in a resource-limited environment (with a minimum of waste)?
- What are the minimum ecosystem requirements to indefinitely sustain a human settlement? (i.e. What is the maximum carrying capacity of an isolated habitat, and of the earth?)

A number of secondary scientific questions emerge from these primary questions:

- What foods can mitigate the effects of microgravity and space radiation on the crew?
- How are critical microbial ecosystems affected by space radiation and microgravity conditions?
- How does plant phenotype and nutritional content depend on spectral content of light and nutrient supply?
- How are plants and seeds affected by space radiation? What level of shielding, if any, is required for a certain level of reliability on the moon and Mars? [Builds on Tomatosphere experience.]
- Are there psychological benefits to the crew of growing green plants in a remote habitat? E.g. The knowledge that a settlement can be self-sustaining, if there is potential for delays or indefinite disruption of Earth-based food supply.

(40) RQ-40: Can we develop food growing technology to the point where we can grow food on the Moon?

(41) RQ-41: Can pulse-based nutraceuticals and/or probiotics provide effective dietary countermeasures for health problems, especially muscle atrophy-based problems and cardiovascular health?

4.2.4.3 Advanced Crew Medical Systems

Future human spaceflight missions will extend considerably beyond LEO. This will mean reduced, if not zero, opportunity for the quick return of a sick or injured crewmember back home for medical treatment. Also, the missions will face considerably increased communications delays between the Crew Medical Officer (CMO) and the ground based Flight Surgeon (FS), and therefore ground-based medical support will be at times impossible. This isolation will require a change in medical support capabilities, from dependence on home base to that of medical autonomy. Increased medical autonomy will be accomplished through the development of an integrated system of advanced technologies, such as, onboard improved sensors, instrumentation, an autonomous medical platform, and integrated crew training.

4.2.4.3.1 Integrated Canadian Approach to Optimize Human Health in Space

The goal is to develop a multidisciplinary Canadian space simulation and research facility (listed in Table 4-8 as FAC-16) in a geographically and geologically appropriate location where there can be a focus on Canadian science and technology development. There are precedents for this sort of facility:

- Hawaii Space Exploration Analog and Simulation (HI-SEAS)
- Human Exploration Research Analog (HERA)
- Self-deployable Habitat for Extreme Environments (SHEE)

4.2.4.3.2 Selected space exploration areas of interest that could be supported

- Psychology;
- Physiological systems/exercise;
- Life-support systems;
- Extreme environmental medical capabilities;
- Food/plant growth;
- Operational studies;
- Geology;
- Technology testing;
- Astrobiology.

Why have a full-scale integrated facility?

- Heritage: Existing Canadian/CSA expertise in large-scale space mission simulations
- Provides an accurate context in which to test space scientific and technology developments
- Interdisciplinary studies to increase likelihood of access to tri-council funding
- Many opportunities for STEM educational activities (depending on location)

Where could the station be built?

- Geologically accurate analogue site; consider future Moon/Mars landing sites:
    - Impact crater/lava flow/periglacial setting; consult with planetary geology team
- Psychologically accurate analogue site; as isolated as possible
    - High Arctic and/or remote location, minimal vegetation
- Balance costs of travel to site with quality of data returned
    - Arctic best, but very expensive
- Established Mars-analogue sites:
    - Existing research sites from the (former/future) CARN
    - Consider Haughton Crater on Devon Island
- Existing Mars Society-owned (US) Flashline Mars Arctic Research Station – may not be open to collaboration/purchase
- Haughton Mars Project
    - Consider Alberta badlands for Mars-like terrain

Selected examples of projects that could be executed at such a facility:

- Develop and test new methods of food production
- Refine rover technologies and optimize human-robot interfaces
- Work through technology readiness levels for real-time crew bio-monitors and sensor systems (radiation sensors, physiological parameters, etc.)
- Evaluate the ACMS in an operational environment
- Evaluate novel remote, telemedical, and telesurgical technologies and capabilities in an isolated environment
- Create and test habitat designs that improve crew wellbeing

- Analyze crew composition and selection criteria to optimize crew functioning (perhaps using multinational crews in collaboration with ISS partners)
- Refine geological sampling and on-site analysis techniques
- Develop key operational space medicine capabilities
- Identify critical diagnostic requirements and develop novel diagnostic technologies and procedures
- Develop evidence-based medical and traumatic treatment protocols and algorithms for use in space and other extreme environments
- Create training programs and high-fidelity simulation exercises that can be used both before and during space missions
- Develop future Canadian experts in operational space medicine through medical education initiatives

Two overarching research questions that could be addressed using FAC-16 are:

(42) RQ-42: What psychological characteristics/competencies make individuals most able to function in isolated extreme and/or Moon/Mars analogue environments?

(43) RQ-43: How can knowledge of psychological characteristics/competencies be leveraged to assist in assembling high-functioning, healthy crews who will experience high cohesion, low conflict, and mission success in isolated extreme and/or Moon/Mars analogue environments?

Addressing these questions adequately requires that we develop a strategy for:

a) leveraging information from existing Canadian research teams in isolated extreme and/or Moon/Mars analogue environments in the Canadian Arctic, and

b) incorporating comparable data collection into subsequent teams and analogue environments, thus

c) allowing for the creation of a statistically meaningful and directly comparable database of team member characteristics, and key team metrics (e.g. health, cohesion, conflict, mission performance).

4.2.4.4 Space Medicine

The purpose of the Space Health TT was to assist the CSA in identifying the key elements required in the future to participate in exciting and challenging human spaceflight activities. One of the TT sub-groups was focused on space medicine, which is an interdisciplinary field concerned with the physical and mental health of astronauts. This space medicine sub-group has outlined the most vital elements below in order of priority. However, it is important to note that the development of these future priorities must be in addition to the essential clinical support currently provided by the Operational Space Medicine office to Canadian astronauts.

(44) RQ-44: Develop key medical capabilities essential for human space exploration, in collaboration with international partners.

(45) RQ-45: Build robust space medicine capacity in Canada.

(46) RQ-46: Integration and translation of past and present life sciences research and operational experience to create individualized crew performance programs for all phases of exploration missions.

Space Medicine clinician-scientists serve as a bridge between the research and clinical communities. Optimization of astronaut health and performance requires translation of basic life sciences research (as detailed in the other sections of this document) into a practical suite of spaceflight countermeasures. The Space Medicine clinician-scientist synthesizes evidence from across multiple physiological and psychological domains into an integrated plan. This ideally would then be individualized to each astronaut, and adapted to a mission's unique demands.

Integration must occur, not only between the physiological and psychological domains, but also temporally, addressing all stages of the astronaut's career and post-career lifespan. Examples of such considerations would include those listed in Table 4-9.

Table 4-9 Astronaut Life Stage and Medical Considerations

Stage	Considerations
Selection	• What are the occupational requirements (physical and psychological)? • Given the available on-mission medical capabilities, which pre-existing medical conditions and/or risk factors should disqualify an astronaut-candidate?
Pre-flight	• What is the optimal preparation plan for a given mission? • Can 'pre-habilitation' mitigate some of the effects of microgravity?
On-mission	• What is optimal combination of countermeasures (i.e. exercise, nutrition, medications, mental health support, etc.) to enhance health and performance across all body systems, without causing undue adverse effects? • What are the acceptable levels of radiation, deconditioning, etc. which can be tolerated without risking the mission or long-term health?
Post-flight	• How may recovery from spaceflight be improved? • What are the significant long-term effects of spaceflight, and how are these best treated?

4.2.5 SH-04: To better understand the psychological effect of spaceflight and develop effective countermeasures

The number of projects funded by the CSA, given below, is small and work on the psychological aspect of spaceflight has been done mostly by the US and USSR/Russia. But there has been more work done in Canada than what CSA has supported, including at least one paper by Norman Endler, and some past work by Peter Suedfeld. Considerably more relevant work has been done if you include analogue and simulation studies such as in Antarctica and the High Arctic. A conference on space and aging was sponsored by CSA and took place in Waterloo (2014).

The psychosocial aspects of spaceflight have many parallels with the psychosocial aspects of aging, pointing to possible funding partnerships with the CIHR Institute for Aging.

Psychological issues that affect crew performance and success are important, especially on interplanetary trips that last for months where there will be no escape from crewmates. There is some overlap with the neurological aspects of Objective SH-03, but beyond eye-hand coordination and perception, the social aspect of the unique isolated conditions of space travel need to be understood. A very important countermeasure to assembling a compatible crew is crew selection; this aspect of space flight is considered under Objective SH-04.

Leveraging the research and technology development from AGE-WELL has a potential to not only advance the development of some elements of an ACMS, but concepts and validation testing developed in the course deploying an ACMS could be spun back to support commercial applications for aging, remote or isolated populations.

In addition to the use of technology, there are many locations where isolation can be studied and understood with the objective of avoiding psychological problems that are applicable primarily to those locations, and secondarily to future space travel and planetary settlement.

(47) RQ-47 Understand isolation issues through the study of life in isolated hamlets, camps, resource extraction sites (mines, logging, etc.); deployed military units; long-stay hospitals and hospices; homes for the aged.

4.2.5.1 Environmental Optimization Systems

Technological countermeasures and optimizers in an isolated, confined, low-stimulation environment would include advanced virtual reality apparatus (e.g. the Oculus Rift virtual reality system), modifiable lighting and sound, movable partitions with variable colours and patterns, and improved provisions for privacy.

(48) RQ-48: Will the development and use of virtual reality apparatus provide a partial countermeasure for the psychological consequences of isolation?

4.2.5.2 Crew Assessment, Psychological/Social Health and Selection

We need to think and communicate about fostering integrative approaches that look at astronauts (and other human beings) as the bio-psycho-social organisms we are. Not only that, but in the case of astronauts, temporal beings: the episode of being an astronaut, and within that the episodes of actual spaceflight, are parts of an ongoing life-span. The experiences must be integrated into one’s total life perspective, including health and well-being of all sorts. Research that only covers brief (or no) follow-ups ignores highly probable changes and possible problems. We need to move beyond our current and “in the pipeline” research and consider major changes or additions. We need to encourage the next generation of space health scientists (our students and early-career colleagues) to think about a new and broader perspective.

Additionally, crew selection is a complex task, which requires an improved understanding of team function in isolated, confined, and extreme environments that simulate the space or planetary environment in question as closely as possible. In order to understand team function over long durations that would approximate a Mars or asteroid mission, additional considerations of team cohesion, conflict, and other metrics over periods of months-to-years are needed.

(49) RQ-49: How will we deal with common social and psychological problems in space and in future planetary colonies? How do we deal with:

- Depression and withdrawal from work and/or social interaction?
- Acute episodes of mania or aggressive behaviour, perhaps requiring restraint?
- Chronic or long-term psychiatric problems?

(50) RQ-50: How can we widen our research and technical innovation beyond problems and countermeasures, to address the enhancement of health, resilience, morale, and task performance above baseline for people who are adequately solving their problems and adjusting to their environment?

(51) RQ-51: What are the priorities in research that integrates questions deriving from all components of the bio-psycho-social human organism in space?

4.2.5.3 Team evaluation and crew selection

Studies of teams leading to an improved understanding of team function and crew selection are needed to support planning for future long-duration missions to Mars, asteroids, or other solar system destinations. NASA’s Human Research Roadmap has identified four “Gaps” within this research area:

- **Team Gap 1:** We need to understand the key threats, indicators, and evolution of the team throughout its life cycle for autonomous, long duration and/or distance exploration missions;
- **Team Gap 2:** We need to identify a set of validated measures, based on the key indicators of team function, to effectively monitor and measure team health and performance fluctuations during autonomous, long duration and/or distance exploration missions;
- **Team Gap 4:** We need to identify psychological measures that can be used to select individuals most likely to maintain team function for autonomous, long duration and/or distance exploration missions;

- **Team Gap 8:** We need to identify psychological and psychosocial factors, measures, and combinations thereof that can be used to compose highly effective crews for autonomous, long-duration and/or distance exploration missions.

(52) RQ-52: Can a protocol be developed for collecting and amassing a meaningful set of data on team functioning in Canadian analogue environments?

We see potential value in examining the behavioural factors that shape and /or predict how well particular combinations of people (e.g. crews) can maintain social harmony and positive working relationships. One approach that may be valuable involves examining the so-called "social signals" that each member sends out by virtue of subtle micro-behaviours (e.g. conversational turn-taking, "mirroring" the behaviour of others, mimicry, variation in speech patterns). These behaviours are difficult to monitor in real-time; however, some evidence suggests that wearable technology in the form of "sociometric badges" may be a useful technology to exploit. Accordingly, we see considerable value in conducting small group research (under various experimental /mission analogue conditions) to determine what can be learned about the impact of crew members' micro-behaviours on crew cohesion, conflict, and general interpersonal functioning.

4.2.6 Systems

Systems and facilities have been given a priority score that is the sum of the priority scores of the RQs that they are associated with. The association between research questions and systems is given in Table 4-10. Given the variable granularity of the RQs plus the fact that it is impossible to be exhaustive in compiling a list of RQs in the face of our ignorance – new knowledge generally generates new RQs – these priority scores must be viewed as very crude. They represent only a very first step that decision makers will have available to them in deciding how to distribute scarce resources.

Table 4-10 Systems Priorities

System		Questions*	Priority Score
Objective SH-01: Radiation			
SYS-01	Bubble detector: Space Personal Neutron Dosimeter (SPND)	3	29.7
SYS-02	Bubble detector: Space Bubble-Detector Spectrometer (SBDS)	4	41.8
SYS-03	Canadian High-Energy Neutron Spectrometry System (CHENSS-II)	13	121.3
SYS-04	DNA-based dosimeter	2	21.2
SYS-05	Canadian Sweeping Energetic Particle Telescope (SWEPT)	5	48.0
SYS-06	Ion mass spectrometers	2	20.6
SYS-07	Cosmic Ray Inspection and Passive Tomography (CRIPT) system	1	12.1
Objective SH-02: Physiology			
SYS-08	Exercise facilities for spaceflight	6	60.72
Objective SH-03: Integration			
SYS-09	Tele-operated surgical robot, Robot Assisted Surgical Training (RAST)	2	22.86
SYS-10	Human Health Research System (HHRS) including a Bio-analysis system, ultrasonic imaging, x-ray imaging, MRI and wearable sensors as subsystems	8	170.42
SYS-11	ACMS	21	191.13
Objective SH-04: Psychology			
SYS-12	Virtual Reality (VR) system for use on the ISS	1	5.41
SYS-13	Sociometric Badges	3	22.04

* Questions" is the number of RQs in this document related to the given system, and rank is the sum over the number of questions and the overall research priorities of those questions.

4.2.7 Facilities

All medical-doctoral research universities have relatively ubiquitous facilities that are useful for space health research and generally available to researchers at those universities. These facilities include general wet labs, animal research facilities and medical imaging facilities. Listed here are the more unique facilities that are ideally available to researchers from any institution, frequently for a fee. The association between RQs and facilities is given in detail in Table 4-11.

Table 4-11 Facilities Priorities

Facilities		Questions*	Priority Score
Objective SH-01: Radiation			
FAC-01	iThemba Laboratory for Accelerator-Based Sciences (iThemba LABS)	3	29.8
FAC-02	National Institute of Radiological Science (NIRS)	3	29.8
FAC-03	ProCure	3	29.8
FAC-04	Los Alamos National Laboratory	3	29.8
FAC-05	Canadian Nuclear Laboratories (CNL)	5	49.8
FAC-06	Bubble Technology Industries (BTI)	3	29.8
FAC-07	Timmins Stratospheric Balloon Base	4	41.8
FAC-08	TRIUMF	3	29.8
FAC-09	McMaster University	3	29.8
FAC-10	NASA Space Radiation Laboratory (NSRL)	7	68.8
FAC-11	Loma Linda University Medical Center	3	29.8
FAC-12	Physikalisch-Technische Bundesanstalt (PTB)	3	29.8
FAC-13	Queen’s University	3	29.8
Objective SH-02: Physiology			
FAC-14	Bedrest Facilities	8	79.50
Objective SH-03: Integration			
FAC-15	Center for Minimal Access Surgery (CMAS)	2	22.86
FAC-16	Multidisciplinary Canadian space simulation and research facility	15	128.75
Objective SH-04: Psychology			
FAC-17	AGE-WELL remote observation and therapy clinics	3	19.53

4.2.8 Canadian companies that participated in the Space Health Topical Team

To be fair to the Canadian aerospace business community, the Space Health TT wants to be transparent in disclosing the businesses that were involved in the creation of the space health part of this document. That disclosure is given here. The Space Health TT included representation from several Canadian companies with an interest in contributing technology toward meeting the space health science objectives. Their input was relevant to assessing Canadian capabilities and strengths. Those capabilities and strengths are partially summarized by their corporate statements, given here. The list is not exhaustive; only the companies that participated in the TT appear here.

(1) Mission Control Space Services

Mission Control Space Services is a relatively new company with interests and expertise in crew psychology. They are interested in conducting studies of teamwork on Moon/Mars analogue missions, to better inform recommendations for crew selection guidelines. Secondly, they are also interested in psychological components of the interactions between crew and robotic assistants, and specifically how a robotic assistant could have beneficial effects on crew mental health.

(2) MacDonald, Dettwiler and Associates Ltd. (MDA)

MDA is a Canadian-based global communications and information company providing operational and robotic solutions to commercial and government organizations worldwide. MDA has performed the role of mission and systems design, development and operation for customers such as the CSA for over 30 years.

Relevant to the TT on Health and Life Sciences, MDA has also developed robotic systems for neurosurgery and image guided interventions. Technologies associated with these projects may have relevance to space-based applications in Operational Medicine or Health and Life Sciences applications.

MDA is interested in

- Mission definition and operational concept development in collaboration with the key stakeholders (CSA, Space Health and Life Sciences researchers, etc.)
- System requirements derivation
- System design and development, and flight qualification with particular interest in systems with an element of robotics or automation

(3) Calm Technologies

CALM Technologies is a designer and manufacturer of specialized equipment for both terrestrial and space applications. The company is currently organized into two operating divisions, which are aligned according to the clients they serve:

- CALMSPACE is our Research and Development division focused on the design and manufacture of space-qualified biological and materials processing systems and is active in System development for the CSA. They have experience collaborating with Engineers and Scientists from NASA, the ESA and Russia’s TsSKB-Progress to deliver quality hardware designed to meet the challenges associated with the harsh environment of space. Systems developed by the CALM Technologies team have flown on the Shuttle, the MIR Space Station, and aboard a FOTON recoverable satellite launched on the Russian Soyuz rocket.
- CALMTECH is a commercial division focused on the design and development of new technology products for use in residential, commercial and institutional applications. Servicing the health care, manufacturing and the home electronic industries, CALM has developed a number of products for a wide range of applications.

(4) Hexoskin

Hexoskin is a global leader in smart clothing for health monitoring. The Hexoskin connected platform provides a new, convenient way to understand human health in real-life environments.

Hexoskin is involved in wearable and mobile health technologies since 2006. Hexoskin's main R&D focus is the development of innovative body-worn sensors for health, mobile, and distributed software for health data management and analysis. Hexoskin users include defense and aerospace agencies, such as the US Navy Medicine, the Australian Army, RCMP, the CSA, and NASA, in addition to hundreds of health researchers and professionals in more than 15 countries.

Hexoskin's mission is to record and organize personal health information and make it accessible and useful. The Hexoskin connected platform architecture includes body-worn sensors, mobile and web apps, a cloud-based database and data analysis server.

Hexoskin is involved in Life Science Research for Space missions since it started working with the CSA in 2011 to deliver a wearable remote health monitoring system and simulation software, the Astroskin. Since then, Carré has worked with people from multiple CSA groups, the NASA and the CNES. Carré, in conjunction with highly qualified consultants, prepared a conceptual study of a bio-monitoring research system for the ISS.

(5) Honeywell/COM DEV International

COM DEV partners with scientists and small businesses to take innovative ideas and technologies and develop precision high reliability instruments for space applications. They have the proven capability to develop system requirements, and end-to-end design, manufacturing and assembly plans for these systems. They also work with the CSA to develop mission opportunities in support of these applications. Now as a part of Honeywell Aerospace, COM DEV has access to a global marketing and sales team that can leverage spin-off technologies to maximize socio-economic benefits of development efforts.

In collaboration with their partners, COM DEV is currently developing a bio-analytics instrument that that will be flown on the ISS and has previously developed mission concepts for a compact MRIr for the ISS, as well as a full scale bioregenerative life support system for a future space habitat with direct application to food security in Canada's northern communities.

(6) Bubble Technology Industries (BTI)

Bubble Technology Industries (BTI) combines scientific, engineering, and manufacturing capabilities to provide advanced commercial, space, and defence solutions in the areas of radiation and explosives detection. BTI provides both cutting-edge products and contract research for prominent clients around the world, including the US Department of Homeland Security (DHS), the US Department of Defense (DoD), various US Department of Energy (DOE) national laboratories, large US defence contractors, and virtually all Canadian federal agencies (including the CSA) involved in radiation detection and counter-terrorism initiatives. BTI's bubble detectors have been used for measurements of neutron radiation in space since 1989 and are now supplied as an ISS payload on a regular basis. Beyond the bubble detector, BTI works with the CSA on CHENSS and CHENSS-II and the Multi-Agent Field Analyzer for Space Applications (MAFASA).

4.2.9 References

- *4.1.3 Funding partners and organizations with an interest space health related research*

  [1] *Hughson, Robertson, Arbeille, Shoemaker, Rush, Fraser, Greaves, "Increased postflight carotid artery stiffness and inflight insulin resistance resulting from 6-mo spaceflight in male and female astronauts", Am J Physiol Heart Circ Physiol, 310:H628-38, 2016.*

  [2] *Steven H. Platts, C. Noel Bairey Merz, Yael Barr, Qi Fu, Martha Gulati, Richard Hughson, Benjamin D. Levine, Roxana Mehran, Nina Stachenfeld, and Nanette K. Wenger. Effects of sex and gender on adaptation to space: cardiovascular alterations. Journal of Women's Health 23 (11):950-955, 2014.*

  [3] *Global Exploration Roadmap, International Space Exploration Coordination Group, August 2013.*

  [4] *Bioastronautics Roadmap: A Risk Reduction Strategy for Human Space Exploration, NASA/SP-2005-6113.*

  [5] *JE Oberg, New Earths: Restructuring Earth and Other Planets, Meridian Books, 1981.*

  [6] *Figure adapted from National Geographic, November 2016.*

  [7] *Ester Boserup has been quoted as saying, "The power of ingenuity would always outmatch that of demand."*

- *4.2.3 SH-02: To better understand biological and physiological changes that occur in reduced gravity environments and to develop effective countermeasures*

  [1] *Lowrey CR, Perry SD, Strzalkowki NDJ, Willams DR, Wood SJ, Bent LR. Selective skin sensitivity changes and senory reweighting following short-duration space flight. J Appl Physiol. 2014; 116(6):683-92.*

5 Acronyms and Abbreviations

AB	Astrobiology	CMAS	Center for Minimal Access Surgery
AC	alternating current	CMB	Cosmic Microwave Background
ACE	Atmospheric Chemistry Experiment	CME	Coronal Mass Ejection
ACMS	Advanced Crew Medical Systems	CMO	Crew Medical Officer
ACS	Advanced Camera for Surveys	CMOR	Canadian Meteor Orbit Radar
ADM	Atmospheric Dynamics Mission	CNES	Centre national d'études spatiales
AGN	Active Galactic Nuclei	CNL	Canadian Nuclear Laboratories
AIAC	Aerospace Industries Association of Canada	COBE	Cosmic Background Explorer
ALMA	Atacama Large Millimeter/submillimeter Array	COLBERT	Combined Operational Load Bearing External Resistance Treadmill
ALS	Advanced Life Support	CorE	Cosmic Origins Explorer
AO	Announcement of Opportunity	COSMOS	Cosmological Evolution Survey
AOGNC	Attitude and Orbit Guidance Navigation and Control	CPSX	Centre for Planetary Science and Exploration
APXS	Alpha Particle X-Ray Spectrometer	CPU	Central Processing Unit
ARC	Astronomy Research Centre	CR	cosmic ray
ASAT	anti-satellite	CRAQ	Centre for Research in Astrophysics of Quebec
ASCA	Advanced Satellite for Cosmology and Astrophysics	CREATE	Collaborative Research and Training Experience
ATHENA	Advanced Telescope for High Energy Astrophysics	CRIPT	Cosmic Ray Inspection and Passive Tomography
AtiLT	Astrobiology Training in Lava Tubes	CSA	Canadian Space Agency
BAO	baryon acoustic oscillation	CSEW	Canadian Space Exploration Workshop
BLSS	Bio-regenerative Life Support System	CT	Computed Tomography
BLAST	Balloon-borne Large-Aperture Sub-millimeter Telescope	DC	Direct current
BRITE	Bright Target Explorer	DFL	David Florida Laboratory
BTI	Bubble Technology Industries	DFN	Desert Fireball Network
CADC	Canadian Astronomy Data Centre	D/H	deuterium-to-hydrogen
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation	DHS	Department of Homeland Security
CAMO	Canadian Automated Meteor Observatory	DIOS	Diffuse Intergalactic Oxygen Surveyor
CAMS	Canadian Astro-H Metrology System	DM	Dark Matter
CAN	Canadian Astrobiology Network	DNA	Deoxyribonucleic acid
CAPS	Canadian Planetary Simulator	DoD	Department of Defense
CARN	Canadian Analogue Research Network	DoE	Department of Energy
CASCA	Canadian Astronomical Society	DTM	Digital Terrain Model
CaSSIS	Colour and Stereo Surface Imaging System	EBEX	E and B Experiment
CASTOR	Cosmological Advanced Survey Telescope for Optical and UV Research	ECCC	Environment and Climate Change Canada
CCD	charge-coupled device	ECLSS	Environmental Control and Life Support Systems
CEVIS	cycle ergometer with vibration isolation and stabilization	ELT	Extremely Large Telescope
CFHT	Canada-France-Hawaii Telescope	EM	electromagnetic
CFHTLenS	CFHT Lensing Survey	EMI	Electromagnetic Induction
CFHTLS	CFHT Legacy Survey	EoR	epoch of reionization
CFI	Canadian Foundation for Innovation	ESA	European Space Agency
CFRP	Carbon Fiber Reinforced Polymer	EVA	Extra Vehicular Activity
CheMin	Chemistry and Mineralogy	ExCore	Exploration Core
CHENSS-II	Canadian High-Energy Neutron Spectrometry System II	Exo-S	Exo-Starshade
CHIME	Canadian Hydrogen Intensity Mapping Experiment	eXTP	enhanced X-ray Timing and Polarimetry
CHRP	Collaborative Health Research Project	FAST	Flights and Fieldwork for the Advancement of Science and Technology
CIHR	Canadian Institutes of Health Research	FGS	Fine Guidance Sensor
CITA	Canadian Institute for Theoretical Astrophysics	FORCE	Focusing On Relativistic universe and Cosmic Evolution
CLASS	Center For Lunar and Asteroid Surface Science	FOV	Field of View
CLS	Canadian Light Source	FS	Flight Surgeon
CLUPI	Close-UP Imager	FTS	Fourier Transform Spectrometer

FUSE	Far Ultraviolet Spectroscopic Explorer	JWST	James Webb Space Telescope
FY	Fiscal Year	LADEE	Lunar Atmosphere and Dust Environment Explorer
G7	Group of 7	LBNP	Lower Body Negative Pressure
G8	Group of 8	LCS	Laser Camera System
GAC	Geological Association of Canada	LEO	Low Earth Orbit
GALEX	Galaxy Evolution Explorer	LIBS	laser-induced breakdown spectroscopy
GC	gas chromatography	LiDAR	Light Detection and Ranging
GCR	Galactic Cosmic Radiation	LIF	laser-induced fluorescence
GCM	General Circulation Model	LOLA	Lunar Orbiter Laser Altimeter
GEM	Global Environmental Multiscale Model	LRP	Long Range Plan
GER	Global Exploration Roadmap	LRPIC	Long Range Plan Implementation Committee
GeV	gigaelectronvolt	LSST	Large Synoptic Survey Telescope
GIS	Geographical Information System	LSSWG	Landing Site Selection Working Group
GOES	Geostationary Operational Environmental Satellite	LUVOIR	Large Ultraviolet Optical Infrared
GOSAT	Greenhouse Gases Observing Satellite	MAC	Mineralogical Association of Canada
GPI	Gemini Planet Imager	MAESTRO	Measurements of Aerosol Extinction in the Stratosphere and Troposphere Retrieved by Occultation
GR	General Relativity	MAFASA	Multi-Agent Field Analyzer for Space Applications
GRASP	Gravitational Asteroid Surface Probe	Ma_MISS	Mars Multispectral Imager for Subsurface Studies
HabEx	Habitable Exoplanet Imaging Mission	MARES	Muscle Atrophy Research and Resistance Exercise System
HD	Hydrogen deuteride	MASTCAM-Z	Mast-mounted camera system with zoom function
HD-AGG	High-Definition Airborne Gravity Gradiometer	MatISSE	Maturation of Instruments for Solar System Exploration
HDO	hydrogen-deuterium oxide	MATMOS	Mars Atmospheric Trace Molecule Occultation Spectrometer
HEA	High Energy Astrophysics	MAVEN	Mars Atmosphere and Volatile Evolution
HERA	Human Exploration Research Analog	MCR	Mission Consolidation Review
HEX-P	High Energy X-ray Probe	MDA	MacDonald Dettwiler and Associates
HHRS	Human Health Research System	MEPAG	Mars Exploration Program Analysis Group
HIFI	Heterodyne Instrument for the Far Infrared	MESSENGER	Mercury Surface, Space Environment, Geochemistry, and Ranging
HI-SEAS	Hawaii Space Exploration Analog and Simulation	MET	Meteorological Station
HPAD	Hybrid Pixel Array Detector	MIDEX	Medium-Class Explorers
HQP	Highly Qualified Personnel	MITACS	Mathematics of Information Technology and Complex Systems
HST	Hubble Space Telescope	MMOD	Micrometeoroid and Orbital Debris
IFC	Integral Field Channel	MOLA	Mars Orbiter Laser Altimeter
IHEP	Institute of High Energy Physics	MOST	Microvariability and Oscillations of Stars
IMU	Inertial Measurement Unit	MRI	Magnetic Resonance Imaging
INO	National Optics Institute	MS	mass spectrometry
IP	International Partner	MSFC	Marshall Space Flight Center
IR	Infrared	MSI	McGill Space Institute
IREx	Institute for Research on Exoplanets	MSL	Mars Science Laboratory
IRMS	Isotope-ratio mass spectrometry	MTR	Mid-Term Review
ISEM	Infrared Spectrometer for ExoMars	NASA	National Aeronautics and Space Administration
ISM	interstellar medium	NCAR	National Center for Atmospheric Research
ISRO	Indian Space Research Organisation	NEA	Near Earth Asteroid
ISRU	In Situ Resource Utilization	NeMO	Next Mars Orbiter
ISS	International Space Station	NEOSSat	Near-Earth Object Surveillance Satellite
ISXRD	in situ X-ray Diffraction instrument	NEX-SAG	Next Orbiter Science Analysis Group
IVIGMS	Integrated Vision, Imaging and Geological Mapping Sensor	NICER	Neutron star Interior Composition Explorer
IVS	Integrated Vision System	NIR	Near Infrared
IXPE	Imaging X-ray Polarimetry Explorer	NIRISS	Near Infrared Imager and Slitless Spectrograph
JAXA	Japan Aerospace Exploration Agency	NIRPS	Near Infra-Red Planet Searcher
JPL	Jet Propulsion Laboratory	NIRS	National Institute of Radiological Science
JUICE	Jupiter Icy moons Explorer	NOMAD	Nadir and Occultation for MArs Discovery

NRC	National Research Council	SE	Space Exploration
NRCC	National Research Council of Canada	SETI	Search for Extraterrestrial Intelligence
NSERC	Natural Sciences and Engineering Research Council	SHEE	Self-deployable Habitat for Extreme Environments
NSRL	NASA Space Radiation Laboratory	SKA	Square Kilometer Array
NuStar	Nuclear Spectroscopic Telescope Array	SLS	Space Launch System
OLA	OSIRIS-Rex Laser Altimeter	SMEX	Small Explorers
OSSO	Outer Solar System Origins	SNe	Supernovae
OST	Origins Space Telescope	SNLS	Supernova Legacy Survey
PanCam	Panoramic Camera	SNR	signal-to-noise ratio
PandAS	Pan-Andromeda Archaeological Survey	SNR	Supernova remnant
Pan-STARRS	Panoramic Survey Telescope and Rapid Response System	SOIR	Solar Occultation at Infrared
PAT	Planetary Atmospheres	SOMN	Southern Ontario Meteor Network
PCLSS	Physico-chemical Life Support Systems	SP	Self-Potential
PDF	Postdoctoral Fellow	SPE	Solar Particle Event
PDS	Planetary Data System	SPICA	Space Infrared Telescope for Cosmology and Astrophysics
PGE	Platinum Group Element	SPICAM	Spectroscopy for Investigation of Characteristics of the Atmosphere of Mars
PGGP	Planetary Geology, Geophysics, and Prospecting	SPICAV	Spectroscopy for Investigation of Characteristics of the Atmosphere of Venus
PHAT	Panchromatic Hubble Andromeda Treasury	SPIRE	Spectral and Photometric Imaging Receiver
PICASSO	Planetary Instrument Concepts for the Advancement of Solar System Observations	SPND	Space Personal Neutron Dosimeter
PIXE	Particle-Induced X-ray Emission	SPIRou	SpectroPolarimètre Infra-Rouge
PIXL	Planetary Instrument for X-Ray Lithochemistry	SSERVI	Solar System Exploration Research Virtual Institute
PolSTAR	Polarization Spectroscopic Telescope Array	SSHRC	Social Sciences and Humanities Research Council
POMM	Polarimètre de l'Observatoire du Mont-Mégantic	STDP	Space Technology Development Program
pptv	Parts per Trillion by Volume	STDT	Science and Technology Definition Team
PRAXyS	Polarimeter for Relativistic Astrophysical X-ray Sources	STEM	Science, Technology, Engineering and Mathematics
PSE	Planetary Space Environment	SWEPT	Sweeping Energetic Particle Telescope
PSLV	Polar Satellite Launch Vehicle	SWIRL	Surface Water Investigation with Raman LiDAR
PSTAR	Planetary Science and Technology from Analog Research	SXS	Soft X ray Spectrometer
PTB	Physikalisch-Technische Bundesanstalt	TAO	Transient Astrophysics Observer
QED	quantum electrodynamic	TBD	To Be Determined
RAST	Robot Assisted Surgical Training	TCC	Trace Contaminant Control
R&D	Research and Development	TECP	Thermal and Electrical Conductivity Probe
RCMP	Royal Canadian Mounted Police	TEMMI	Three-Dimensional Multispectral Microscopic Imager
REMS	Rover Environmental Monitoring Station	TESS	Transiting Exoplanet Survey Satellite
RGB	Red Green Blue	TeV	tera electron volt
RIMFAX	Radar Imager for Mars' Subsurface Experiment	TGO	Trace Gas Orbiter
RIS4E	Remote In Situ and Synchrotron Studies for Science and Exploration	TMT	Thirty Meter Telescope
RLS	Raman Laser Spectrometer	TREX	Toolbox for Research and Exploration
RMGG	Rover Mounted Gravity Gradiometer	TRL	Technology Readiness Level
RNA	Ribonucleic acid	TT	Topical Team
ROM	Royal Ontario Museum	TVIS	Treadmill with Vibration Isolation and Stabilization System
RQ	Research Question	U.	University
RSL	Recurring Slope Linea	UAE	United Arab Emirates
SAA	South Atlantic Anomaly	UARS	Upper Atmosphere Research Satellite
SAFARI	SpicA FAR-infrared Instrument	USA	United States of America
SAGE	Stratospheric Aerosol and Gas Experiment	USD	United States Dollars
SAO	Smithsonian Astrophysical Observatory	USSR	Union of Soviet Socialist Republics
SAR	Synthetic Aperture Radar	UV	Ultraviolet
SBDS	Space Bubble-Detector Spectrometer	UVIT	UltraViolet Imaging Telescope

VASIMR	Variable Specific Impulse Magnetoplasma Rocket		
VEGA	VEctor Gravimeter/Accelerometer		
VIIP	Vision Impairment Intracranial Pressure		
VIS	Visible		
VLT	Very Large Telescope		
VR	Virtual Reality		
WFC	Wide-field Channel		
WFI	Wide Field Imager		
WFIRST	Wide Field Infrared Survey Telescope		
WHIM	Warm-Hot Intergalactic Medium		
WINDII	Wind Imaging Interferometer		
WL	weak gravitational lensing		
WMAP	Wilkinson Microwave Anisotropy Probe		
WRF	Weather Research and Forecasting		
XARM	X-ray Astronomy Recovery Mission		
X-IFU	X-ray Integral Field Unit		
XIPE	X-ray Imaging Polarimetry Explorer		
XRD	X-ray Diffraction		
XRF	X-ray Fluorescence		