Canadian Scientific Priorities
for the
Global Exploration Strategy

Potential Canadian science and medical contributions to the exploration of the Moon, Mars and beyond, developed from the proceedings of the 6th Canadian Space Exploration Workshop (CSEW6) held at the Canadian Space Agency's headquarters, December 1-3, 2008

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CSEW6 Steering Committee*

**See Appendix 1 for names and affiliations.* Requested citation:
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Executive Summary

As humanity looks beyond Earth to other planets and moons, the science and technology required to realize missions to these bodies must be developed. Canada is uniquely positioned to take a leading role in several areas because we have already tackled some of the problems of performing studies in extreme environments. The Canadian extreme environment is the Arctic, where developing resources and communities require well thought-out solutions to the problems of harsh conditions, remoteness and limited communications.

Canadian scientists also have the advantage that they are already familiar with space science and technology through a number of programs. In September 1962, Canada launched the Alouette-I spacecraft, thus making it the third nation in space after the US and Russia. More recently, Canada has been involved in major robotic missions and manned operations on the International Space Station (ISS). Canadian science and industry are well positioned to make major contributions to space-related endeavours as humanity advances beyond Earth.

In December 2008, a large group of Canadian scientists came together with representatives from both industry and government to consider the potential for Canadian science activities beyond the vicinity of Earth. From discussions at that meeting (the 6th Canadian Space Exploration Workshop (CSEW6)), and many discussions afterwards, a number of extremely promising directions have been identified within the following disciplines:

- astrobiology
- advanced life support
- Mars atmospheric studies
- operational space medicine
- planetary geology and geophysics
- radiation effects on humans
- solar terrestrial science
- space astronomy
- space life sciences
- space physical sciences

Some of these research areas, such as operational space medicine, are concerned with the health of astronauts. Others, such as space astronomy, deal with the opportunities afforded by being in space. Still others, such as Mars atmospheric studies, are concerned with the *in situ* science that can be accomplished on moons and planets in the solar system.

Within each research area, a number of objectives have been identified; a number of possible investigations are suggested for each. In every case, there is already an established cadre of Canadians who are contributing (or able to contribute) to

international efforts. In many cases these Canadians are already making major contributions and the benefits are felt in Canadian society beyond the space-related activities that initiated them. These activities cover a wide range: from studies of radiation effects on humans to the search for extra-terrestrial planets; from rocks on the moon to the rarified plasma surrounding the planets; from growing food in space to the weather on Mars; and from seeking life in the universe to preserving the lives of astronauts.

Sometimes the space activities are intimately linked to endeavors for the benefit of Canadians; for example, tele-medicine (including robotic applications) needed to maintain the health of our Northern populations. Sometimes space missions are the primary activity; for example, the extremely successful meteorological package on the Phoenix Mars Lander mission. In all cases, these are actual world-leading activities or have the potential to be so.

Space activities involve significant investments, and therefore require considerable preparation to maximize the benefits to science and the technological advances that can be achieved on each mission. Analogue studies are activities that can be performed in advance of a mission to mitigate the risks. These analogue activities may be laboratory-based, or may be field activities at locations on Earth that resemble conditions on other planets. Some of these analogue sites are found in Canada’s Arctic. There is international interest in accessing these research venues. Analogue activities pave the way for future robotic missions, such as rover missions to the moon and Mars, or for human exploration of the planetary system. Beyond that, space missions in Earth orbit, such as the Canadian SCISAT mission, can act as full dress rehearsals for similar planetary missions.

The consultations among Canadian stakeholder groups culminating in CSEW6 have clearly identified a number of areas where Canada can make a unique contribution to global activities in space exploration as outlined in the Global Exploration Strategy (of which Canada is a co-author) in a way that meets the goals of Canada’s Science and Technology Strategy. In addition, consultation activities have brought together a distinguished and enthusiastic community committed to achieving these goals.

The main benefits to Canada of participation in space exploration missions beyond Earth orbit are:

- Gaining scientific knowledge: Knowledge is the basis of innovation and progress.
- Accelerated development of cutting-edge technologies that will not only support these missions but also provide spin-offs to the general economy. Innovation is key to economic success.
- Generating interest in science and technology in young people from elementary school to university and beyond.

Space exploration beyond Earth orbit is beyond the capacity of any single nation. By highlighting the potential for Canadian contributions to global space exploration activities, the authors of this report hope to encourage the implementation of a consistent, long-term program that will realize the goals identified here.

Introduction

In May 2007, fourteen space agencies, including the Canadian Space Agency, signed the Global Exploration Strategy (http://www.asc-csa.gc.ca/pdf/global_exploration.pdf), signifying the beginning of a new era of global cooperation in space exploration.
Its vision is the exploration of solar system targets (Moon, Mars, asteroids, and in the very far future, outer planetary moons) where humankind may one day live and work. The Global Exploration Strategy expresses high-level consensus regarding the ways that civilian access to space advances national interests. It is a framework that understands that countries will continue to advance national interests, but expresses the intent of members to share information, minimise duplication of missions, and collaborate in areas of common interest. It recognises that no single nation can afford to make the next steps in human space exploration alone.

Human exploration will start with the International Space Station in low Earth orbit, then the Moon, then go on to Mars and the asteroids. In the very far future, humanity may even reach some cold (but water-rich) moons around the outer planets. A long journey, but humanity will reap its benefits long before it ends. The knowledge we hope to gain from the exploration of—and from—these targets, as well as preparing ourselves for long-duration spaceflight, should advance fundamental learning about ourselves, our world, our solar system and the worlds beyond.

This document describes potential Canadian scientific contributions to the Global Exploration Strategy. It is organized in ten chapters, beginning with disciplines largely concerned with understanding planets (astrobiology; Mars atmosphere; planetary geology and geophysics; and solar-terrestrial physics); including space astronomy (representing science using the Moon as a platform). It ends with scientific and medical disciplines that will enable future human exploration (advanced life support; operational space medicine; space life sciences; radiation; and space physical sciences).

Each chapter shares a similar layout: an introduction to the theme, summary of objectives, and a detailed description of each objective followed by a number of investigations.

Objectives and investigations are referenced as follows:

AB=astrobiology
ALS=advanced life support
AT=atmospheric science
OSM=operational space medicine
PG=planetary geology & geophysics
RAD=radiation
SA=space astronomy

SLS=space life sciences
SPS=space physical sciences
ST=solar terrestrial sciences

References are given as discipline-(planet)-objective investigation, where targets are L=moon, M=Mars, S=small bodies (outer-planet moons and asteroids)

There is no attempt to prioritize one discipline over another, since, for example, scientific understanding of life, atmosphere and geology is interrelated, and human exploration similarly requires advances in all areas. Within each discipline, objectives describe long-term milestones, while investigations describe strategies to advance them. Some disciplines also include a roadmap as a logical path linking several high-priority objectives and investigations with technologies and mission concepts. For other themes, identification of technologies and mission concepts that respond to objectives has been left as a task for future readers to inspire innovation.

Cross-cutting themes have not yet been fully identified, but two examples are provided here that signify a potential for long term synergistic research endeavours:

> The **water ice** environment is an area where the Canadian North is a natural laboratory, and in which Canadians have much expertise. It appears as a target of numerous objectives and investigations**:** as solar system history (PG-L-3,PG-S-2); a habitable environment for life (AB-3,-5, PG-M-1); climate tracer (AT-M-1,2); landform features (PG-M-1;PG-S-2); *in situ* resource (PG-L-3, PG-M-1); mapping (AT-M-1, AT-M-2.5, PG-L-3.1,3.2, PG-M-1.1,1.2, PG-S-2.1); drilling (AB-5.4, AT-M-2.5, PG-M-1.4); *in situ* analysis (AB-5, AT-M-1, AT-M-2.5, PG-L-3.3, PG-M-1.3); modelling (AT-M-1.7, PG-S-2.2); and analogue activities (AB-3.1, AB-5, AT-M-1.8, 2.7, PG-L-3.4, PG-M-1.4, PG-S-2.3)
>
> **Protecting humans from space radiation** is a theme that cross-cuts science and medical disciplines: space weather(ST-L-2, ST-M-3); planetary magnetism (PG-L-5, PG-M-3, PG-S-1,ST-M-1); damage by radiation to biology (ALS-2.1, OSM-5, SLS-1, SLS-5, RAD-3, SPS-4, SPS-5); medical mitigation (SLS-1.3, RAD-3); radiation shielding (ST-L-3.3,ST-L-3.3,ST-M-3.1, RAD-2, SPS-10); mapping (PG-L-5.1, PG-M-3.4, 3.5); sample return (PG-L-5.1); modelling/prediction (ST-L-3.1,ST-M-3.1, RAD-2); *in situ* analysis (PG-L-5.2, ALS-2.1, OSM-5, SLS-5, RAD-1); and analogue/ground-based activities (SLS-1.1,SLS-1.2, RAD-2, RAD-3, SPS-10)

Following the workshop, discipline working groups took on the challenge of developing results into content for this document. The appendices provide details and affiliations of all people who have contributed.

Appendix 1: CSEW6 steering committee
Appendix 2: Membership of the various discipline working groups.
Appendix 3: Participants at CSEW6

1 1. Astrobiology

The primary focus of astrobiology is to search for evidence of life beyond Earth. It is a multidisciplinary field that includes biologists, Earth and planetary scientists, astronomers and engineers. It encourages synergies between disparate sciences and technologies, enriching all the fields involved and contributing to the development of Canada's scientific and engineering base and future economic health.

Astrobiology also commands tremendous public interest, in large part because it addresses some of the most basic questions of human existence: who are we? Where do we come from? And are we alone? For the first time in history, we have the technology to be able to explore these questions scientifically.

There are three major streams of astrobiological research that can exploit the current skills and capabilities of Canada's astrobiology community:

- to determine the limits of life, including the range of physical and chemical conditions under which life could arise and persist
- to determine the origin of life on Earth and generate sufficient insight to extrapolate to origin(s) on other planets
- to determine the existence of extraterrestrial life, either extinct or extant.

The first two questions are key to addressing the third; the origins and limits of life can help scientists select extraterrestrial sites that offer the most promising targets to search.

The Canadian astrobiology community is strongly committed to expanding Canada's contribution to a worldwide effort to advance scientific knowledge about extraterrestrial life. Participating in space missions is a high priority. Mars is of primary interest, but not to the exclusion of other significant targets like the Moon and Europa, Enceladus and Titan, moons of Jupiter and Saturn. It is also critical to conduct studies at Earth-based analogue sites that simulate important aspects of extraterrestrial environments.

Canada should pursue a diverse and dynamic astrobiology research and development program that includes developing flight-ready scientific instruments for astrobiological investigations of planetary surfaces and subsurfaces, and testing these technologies at analogue sites. This will provide an opportunity for Canada to capitalize on its existing expertise in advanced robotics.

Summary of Objectives

- AB-1 Detect the presence of potentially habitable environments on other planets, including exoplanets (planets outside our solar system).

- AB-2 Capitalize on Canada’s experience in developing flight instrument hardware by developing instruments for astrobiology investigations.
- AB-3 Exploit Canada’s diverse planetary analogue environments, both modern and ancient, to discover and investigate organisms that live in extreme environments and the limits to their survivability and growth.
- AB-4 Exploit Canada's diverse planetary analogue environments to develop an understanding of the formation and preservation of biosignatures and develop life detection instruments for flight.
- AB-5 Search for direct evidence of extinct or extant life through biosignatures by developing methodologies and instruments for *in situ* investigation of planetary environments, and validate their operational performance in operational contexts at Canadian analogue sites.
- AB-6 Analyze samples from planetary sample-return missions for the presence of preserved or existing life.
- AB-7 Advance planetary protection policy and implementation.
- AB-8 Support intellectual interest in astrobiology in Canada, linking to other areas of astrobiology (e.g. remote life detection on other planets).

Objectives and Investigations

Objective AB-1: Detect the presence of habitable environments on other planets, including exoplanets (planets outside our solar system).

Decades of sending space probes throughout the solar system has produced a wealth of data about conditions on the planets and moons in our solar system. Using advanced telescopes, scientists have also discovered about 300 planetary systems beyond our solar system. Most of the planets found so far are much more massive than Earth; they resemble Jupiter or Neptune and do not have rocky surfaces.

However, scientists have also found several planets with masses only a few times that of Earth, including one at about twice Earth’s mass that may have a rocky surface. With improvements in telescopes, they expect to be able to see smaller, more Earth-like planets in the future.

Data from these discoveries are helping astrobiologists evaluate the potential of extraterrestrial sites that might harbour life and design future missions to search for life.

Investigations:

1. Develop theories, models and methods to quantify the ability to develop and sustain life (habitability) of planetary environments.
2. Determine the habitability of environments on Mars and other planetary bodies through analysis of planetary and astronomical data.

Objective AB-2: Capitalize on Canada’s experience in developing flight instrument hardware by developing instruments for astrobiology investigations.

Investigations:

1. Build on our understanding of biosignatures in order to select measurement strategies and develop instruments.
2. Develop and test miniaturized instruments for *in situ* analysis.
3. Develop and test instruments for determining the geological context of samples and measurements, including the chemical and mineral contents of materials and the geological processes that emplaced them.

Objective AB-3: Exploit Canada’s diverse planetary analogue environments, both modern and ancient, to discover and investigate organisms that live in extreme environments and the limits to their survivability and growth.

There are a number of sites in Canada, known as analogue environments, that can be used to simulate conditions on other planets. The Arctic, for example, can stand in for the cold Martian surface. Hydrothermal vents off the coast of British Columbia provide an opportunity to study organisms that can survive a very hot and chemically toxic environment. By studying organisms that live in these harsh environments on Earth, scientists can gain a better understanding of how organisms might be able to survive extreme conditions on other planets.

Investigations:

1. Determine the lower temperature limits to life on Earth.
2. Determine limitations to survivability and growth on early Earth, and the chemical and atmospheric conditions under which life originated on Earth, to improve strategies to search for life elsewhere.

Objective AB-4: Exploit Canada's diverse planetary analogue environments to develop an understanding of the formation and preservation of biosignatures and to develop life detection instruments for flight.

Biosignatures refer to physical, chemical, isotopic or mineral traces in the rock that record the past presence or activity of organisms. By detecting and analyzing these traces, researchers can determine some of the properties of that biological activity. Many of the biological organisms that might be expected in extraterrestrial environments may resemble those that flourish in extreme terrestrial environments, such as the Canadian Arctic.

Investigations: Different environments and geological settings can provide information on different biosignatures. A comprehensive approach to investigating the formation of biosignatures (in modern systems) and preservation (in ancient systems) should address the following:

1. Macromolecular signatures relevant to microorganisms, such as biological residues of cyanobacterial cell walls (hopanoids)
2. Mineralogical signatures such as microfossils, biominerals and biosedimentary structures
3. Isotopic signatures: for example, carbon isotope ratios may in some cases be diagnostic of biological activity
4. Develop a set of standard reference samples relevant to a planetary target and that can be used to test and compare methodologies and instrument techniques for biosignature analysis.

Objective AB-5: Search for direct evidence of extinct or extant life through biosignatures by developing methodologies and instruments for *in situ* investigation of planetary environments, and validate their operational performance in operational contexts at Canadian analogue sites.

It is necessary to develop methodologies and instruments to detect biosignatures in planetary environments. There are many different types of biosignatures, but each requires a specific mode of detection which determines the type of instruments that must be developed (for example, Raman spectroscopy for hopanoids or tuned diode laser absorption spectroscopy for carbon isotope ratio measurements).

Investigations:

1. Detect cells on Mars as an unambiguous criteria for life detection.
2. Quantify and search for atmospheric biosignatures on Earth, Mars and exoplanets.
3. Determine the source of methane recently detected on Mars.
4. Access Martian subsurface environments to search for buried biosignatures, as such deposits are protected from exposure to damage on the surface.
5. Use the Moon as a negative control (that is, a place where no life is present).
6. Consider non-earth-centric life forms. Terrestrial organisms employ DNA, RNA and proteins to implement life, but is this the only way?

Objective AB-6: Analyze samples from planetary sample-return missions for the presence of preserved or existing life.

The international space community is planning to send probes to Mars that will be capable of returning rock and soil samples to Earth. Canada’s astrobiology community should be prepared to contribute to those missions and participate in analyzing these samples for evidence of life.

Investigations:

1. Subject biological samples to the range of laboratory analysis available in Canada
2. Develop isolation facilities in Canada for the remote, robotic handling of potential biological samples from sample-return missions
3. Develop and test cutting-edge, ground-based laboratory analytical and imaging facilities for detailed investigations of returned samples.

Objective AB-7: Advance planetary protection policy and implementation.

Before any extraterrestrial life is found, it is necessary to put policies in place to protect both Earth and extraterrestrial sites from biological contamination. When sending spacecraft to other planets, it is important to ensure that terrestrial organisms do not hitch a ride. This kind of contamination could compromise future searches for extraterrestrial life and, if such life exists, could potentially damage it. At the same time, it is important to protect Earth and its life forms from contamination by extraterrestrial organisms that may be found in samples returned from other planets.

Investigations:

1. Develop and test protocols limiting forward biological contamination of extraterrestrial sites to preserve habitable environments for future life-detection experiments
2. Develop and test sample handling protocols and investigations for samples returned to Earth to ensure that extraterrestrial organisms cannot create a biological hazard on Earth.

Objective AB-8: Support intellectual interest in astrobiology in Canada, linking to other areas of astrobiology (e.g. remote life detection on other planets).

Roadmap

In order to achieve the goals described above, Canada should develop a three-pronged strategy to explore the origins of life in the solar system and beyond. The major elements of this strategy include:

- a commitment to studies of analogue environments on Earth
- robotic exploration of Mars and in future, involvement in missions to the icy moons of the solar system and
- astronomical research to discover super-Earths (planets a few to ten times the mass of Earth).

The exploration of Mars for signs of life is a key component of astrobiology. Future robotic missions may investigate aspects of the Martian environment that are significant for life (for example, regions with evidence of water ice, methane production, etc.). Canada's scientific community and Canadian industry have important strengths in this field and it is essential for them to be involved in major international exploration programs in the coming decade if they are to have a major impact in this area.

To promote its participation in these missions, Canada should develop flight-qualified, *in situ* astrobiological instrument suites; robotic field astrobiologist intelligence systems; and robotic sample acquisition and processing systems. These instruments should be deployed and tested at Canadian analogue sites that can stand in for extraterrestrial sites. The samples recovered from these sites should be subjected to stringent remote-handling laboratory analysis in Canada. This would test the ability of Canadian labs to analyze samples returned from extraterrestrial sites.

A significant effort is required to develop a greater understanding of the formation and preservation of different biosignatures in environments relevant to Mars. We must also develop strategies and instruments to search for, detect and quantify these biosignatures. This will require a major collaborative effort within the astrobiology community. For example, one major issue concerns whether methane gas detected on Mars is biological in origin, and if so, whether it is ancient or contemporary.

The third major thrust for astrobiology is on the astronomical side. The discovery of super-Earths (planets with a few to ten times the mass of the Earth) around low-mass stars has demonstrated that rocky planets similar to the Earth exist. The Canadian Space Agency has invested in the search for exoplanets through its support for the MOST small satellite. It has also strongly supported the Canadian astronomical community through involvement in the James Webb Space Telescope (JWST).

Space-based observatories have and will make enormous contributions to the search for exoplanets and characterizing rocky planets that may bear life. Understanding the biosignatures of life that could be detectable in planetary atmospheres is an important area for interaction between astronomers and microbiologists interested in astrobiology.

The launch of the Kepler satellite in March 2009 also has enormous ramifications for this field. Kepler will monitor around 100 000 stars to detect Earth-like planets that are orbiting their central stars within their habitable zones. Here again, the Canadian astrobiology community has much to contribute if it can engage in an astrobiology program linking the microbiology and exploration communities with these astronomical studies.

The Canadian community should also seriously consider involvement in future projects, such as the Terrestrial Planet Finder, a mission concept currently being considered by NASA that may be developed in the coming decade.

Canadian astronomers will continue to be involved in projects to study extrasolar planetary systems, including searching for terrestrial planets. This community will be potentially very interested in astrobiology.

In summary, the time scale to achieve the goals of the astrobiology community includes:

Short-term goals:

- Determine the astrobiological instruments for robotic *in situ* measurements on planetary exploration missions
- Test these devices under Mars analogue conditions on Earth and
- Address the issue of forward contamination.

Medium-term goals:

- Develop technologies to identify, acquire and analyze samples on Mars that will ensure the selection and return of samples with a high scientific value. A "grab bag" philosophy cannot be justified, given the cost of returning samples to Earth.

Long-term goals:

- Return samples from Mars for detailed laboratory analysis on Earth
- Develop effective sample-handing techniques and forward and reverse planetary protection procedures to protect against biological contamination on Earth and on other planets
- Develop expertise in ground-based, remote-science operations and science team operations. Build capacity, including expertise and highly-qualified personnel.

2 Mars Atmosphere

The atmosphere of Mars is always of great significance in any exploration mission to the planet. It is important to study the atmosphere not only to advance scientific knowledge of the solar system, but also for practical reasons: understanding the Martian atmosphere is essential for landing vehicles on the surface and maintaining both robotic and human operations once there.

Answering some of the key scientific questions about Mars (notably those concerning the presence of liquid water and the possibility that the planet has or could support life) requires knowing more about the atmosphere, not only in its present state but how it has evolved over time.

Scientists are also seeking to understand how the thin Martian atmosphere interacts with the planet's surface and creates its weather, including huge dust storms. This knowledge is also important for future missions to Mars, including eventual human colonization.

Canadian researchers and technology companies are already seriously involved in studies of the Martian atmosphere. The Phoenix spacecraft, which landed on Mars in May 2008, carried a Canadian-built meteorological station with temperature and pressure sensors and a lidar that was the first to be successfully operated on a planetary surface.

Canada has a long history of developing instruments to study Earth's atmosphere. Its considerable scientific and technological expertise in this field can be deployed to make critical atmospheric measurements related to the hydrological cycle on Mars, the evolution of the Martian atmosphere and the interaction between the atmosphere and the surface of Mars.

Canada can take the lead in providing several instruments that could be placed on the Martian surface and in orbit to study a wide range of atmospheric and meteorological parameters including: water vapour and other atmospheric constituents; dust and aerosols (small particles); clouds; precipitation; temperature; atmospheric pressure; winds and radiation fields.

Canada already has significant expertise in developing several types of instruments that could be used in such studies, including: lidars; spectrometers; tunable diode lasers; meteorological instruments; Doppler imaging; particle measurement systems; visible and infrared imagers and radiometers.

Summary of Objectives

- AT-M-1 Investigate atmospheric processes that affect the transport of water on Mars and the exchange of water with the surface.

- AT-M-2 Investigate the evolution of the Martian atmosphere.
- AT-M-3 Investigate the interaction between the atmosphere and the Martian surface.

OBJECTIVES AND INVESTIGATIONS

Objective AT-M-1: Investigate atmospheric processes that affect the transport of water and the exchange of water with the surface of Mars.

Water sources, storage, transport and disposition are critical issues in studies of the past and present habitability of Mars. Research on Martian land formations and soil chemistry provide evidence that the planet had liquid water on its surface in the past. Today, water ice is abundant in the polar caps; they hold an amount of water equivalent to a uniform layer 20 metres deep over the planet. The Odyssey orbiter made the profound discovery of a vast quantity of ice below the surface; this was recently confirmed with surface excavation during the Phoenix Mars Lander mission.

There is a hydrological cycle on Mars in which the atmosphere moves water between widely separated reservoirs. Measurements from orbit have revealed a seasonal cycle in the amount of water in the atmosphere, with the maximum occurring over the northern polar region in summer. Identifying the atmospheric processes that affect the transport of water and exchange with the surface will remain a priority for future exploration missions to Mars.

The Canadian lidar instrument on the Phoenix mission discovered that water-ice crystal precipitation falls on the surface of Mars: in short, it snows, and on a daily cycle. During the day, water vapour is transported upward by turbulence and convection. At night, this water forms clouds of ice crystals that fall back to the surface. This combination of local processes could not be observed from previous orbital and landed missions—it could only be observed by ground-based lidar observations. This discovery alters current understanding of the water cycle on Mars and will stimulate further studies.

Investigations:

1. Measure the vertical profile of atmospheric water vapour, both at landing sites and globally. Since water is always transported through the atmosphere, the water vapour profile is a basic input for all further studies for this objective.
2. Investigate the processes that transport water around Mars, including measurements of atmospheric dynamic variables such as winds. Large-scale transport processes move water vapour between the poles on a seasonal basis.
3. Measure the exchange of water between the atmosphere and the ground. Very little is known about transfer between water embedded in the surface and the atmosphere, but the surface reservoir could be extremely large.
4. Observations of clouds and precipitation at landing sites and globally.

5. Track changes related to the deposition and sublimation of water and carbon dioxide, particularly at the poles. These processes exhibit seasonal changes and may also change over longer periods, providing clues about the evolution of the Martian climate.
6. Measure the size, shape and number density of dust particles and ice crystals. The Phoenix mission demonstrated the importance of considering solids as well as gases.
7. Model the Martian hydrological cycle to interpret and provide context for measurement. Results from many missions are required.
8. Use terrestrial-based testing and analogue environments to advance the ability to interpret data, to develop ground-based and orbital instruments analogous to those needed for Mars and to maintain a pool of experts for future missions.
9. Develop instruments to measure advance properties of aerosols (small atmospheric particles.)

Objective AT-M-2: Investigate the evolution of the Martian atmosphere.

Today, Mars has a thin atmosphere composed primarily of carbon dioxide. Some evidence indicates that the atmosphere was thicker in the past but over time, most of it escaped into space. There are no direct measurements of Mars' past atmosphere, of course; what scientists know about it comes from deciphering the planet's surface features and examining the layers of ice at the polar caps, which also offer a glimpse into planetary history.

Making a direct analogy with Earth, scientists interpret valleys like Valles Marineris as evidence that liquid water once existed on the surface of Mars. Some surface features also suggest that liquid water may have run recently. If that is a correct interpretation, then the Martian atmosphere was once thick enough to create sufficient atmospheric pressure to allow liquid water to exist on the surface.

There is also strong evidence of glaciation in certain areas of Mars. This interpretation has been strengthened by the results of atmospheric modeling that suggest certain regions are prone to generating ice clouds with precipitation. Atmospheric modeling of the impacts of polar wandering (changes in the orientation of the planet's axis of rotation relative to its orbital plane) also predicts a large scale migration of water from the current poles to the equator when the poles' inclination angle to the Sun increases. Further studies in this area will help to show how the distribution of water and ice have changed over time, leading to the present state.

Information about the history of Mars' atmosphere can also be gleaned from measuring ratios of different isotopes (slightly different atomic forms) of the noble gases trapped in rocks obtained from the Viking landers. Different processes result in different ratios of these isotopes. Isotope ratios characteristic of Mars have been found in meteorites on Earth, leading scientists to conclude that these meteorites originated on Mars and were the result of a collision between Mars and a large object that ejected solid material into space. This collision could also have ejected a large fraction of Mars’ atmosphere at that time.

Mars’ atmosphere continues to escape to deep space via several mechanisms, including thermal evapouration, chemical processes, and interaction with the solar wind (charged particles streaming out from the Sun), which can abrade the upper atmosphere.

Investigations:

1. Measure dynamical variables such as temperature, pressure and winds to identify large-scale circulation patterns and transport pathways in the atmosphere. These data can be used to construct an accurate picture of the atmosphere to validate computer models.
2. Measure profiles of the chemical constituents of the present atmosphere, including carbon dioxide, carbon monoxide, oxygen, ozone and many others. These identify the current status of the evolution of the Martian atmosphere. Isotope ratios can indicate the source and history of the components.
3. Measure the composition in the upper levels of the atmosphere. These measurements are important for understanding the processes involved in the escape of Mars’ atmosphere into space.
4. Measure the interaction of the atmosphere with the surface and how much material is exchanged between the two. Understanding conditions in the boundary between the atmosphere and the Martian surface will also require geological measurements and *in situ* measurements by landed vehicles.
5. Map the location and volume of the polar ice caps and changes that occur there. Lander vehicles capable of drilling beneath the surface could collect depth data, including isotope ratios, which would provide a time history of the caps.
6. Model the evolution of the Martian atmosphere leading to its current state. Models can develop an integrated picture of the atmosphere by provide links between sets of measurements. These models should include the regolith (surface rock) as well as the interface between the atmosphere and space.
7. Use terrestrial-based testing and analogue environments to advance the ability to interpret data, to develop ground-based and orbital instruments analogous to those needed for Mars and to maintain a pool of experts for future missions.

Objective AT-M-3: Investigate the interaction between the atmosphere and the Martian surface.

The surface plays a critical role in the energy budget of a planet. It absorbs part of the solar radiation falling on it and emits heat. The surface is the interface across which heat and water are exchanged with the atmosphere. It is also the source and sink of the dust that plays such an important role in weather and climate on Mars.

Water vapour and, in polar regions, carbon dioxide, condense onto and sublime from the surface. This process affects annual cycles of atmospheric pressure and water content on Mars in a major way. As on Earth, the boundary layer of the atmosphere (typically the lowest one to six kilometers on Mars) plays a critical role in the interaction between the surface and the atmosphere as a whole.

During the Phoenix mission, the Canadian-built meteorological station on the lander played a key role in studying interactions between the atmosphere and the surface. The lidar, the first to be used on the surface of an extraterrestrial body, provided unique information on the role of clouds and precipitation in the local water cycle at the Phoenix site north of the Martian Arctic circle. Ice fog was also observed and dust profiles provided new information on atmospheric boundary-layer depth.

Apart from the lidar, the Phoenix meteorological station was rather basic (three temperature sensors and a pressure sensor), but it also obtained some wind data. The Thermal and Electrical Conductivity Probe, designed primarily to measure soil moisture, was used to obtain much-needed information on atmospheric water-vapour pressure.

Despite the successes to date, research on the interaction between the Martian atmosphere and surface is still in its infancy. At present, there are serious limitations associated with Mars landing missions, such as landing locations and duration of measurements. In the future, more sophisticated missions should enable more comprehensive investigations of surface features. Mars offers a wide range of surface types. As the specific characteristics of different regions (e.g. the polar caps) are identified, it is important to treat each region separately and to sample as many locations as possible to refine the scientific understanding of surface-atmosphere interactions.

Investigations:

1. *In situ* measurements of near-surface meteorological parameters such as temperature, pressure, water vapour concentration and wind speed and direction. A meteorological station should be part of any mission landing a spacecraft on Mars. It is important to have continuous measurement throughout every sol (Martian day) for at least one Martian region (even in polar regions). *In situ* wind and turbulence measurements are the most difficult to make on Mars, but are vital to understanding the local atmosphere. Direct measurements of the energy inputs and outputs are also required.
2. Global observations of clouds and precipitation. Imaging clouds and determining the temperature at the top of clouds provides information about the Martian weather. Information on the evaporation and condensation of material in polar regions could be obtained by measuring subtle changes in the surface elevation of the polar regions from orbit-based altimeters and measuring dust and cloud concentrations from above. It might even be possible to capture outbursts of gas and particles from geysers.

3. Local measurements of clouds and precipitation. Data from the Phoenix lander has shown that local events, such as precipitation and boundary-layer effects, can influence the atmosphere/surface interaction.
4. Local-scale modeling, distinct from the larger-scale modeling in which it is embedded. This can show how measurements at a single location can be related to the entire planet.
5. Use terrestrial-based testing and analogue environments to advance the ability to interpret data, develop ground-based and orbital instruments analogous to those needed for Mars and maintain a pool of experts for future missions.

Roadmap

The exploration of the Martian atmosphere is particularly suited to Canadian scientific and industrial expertise because Canadians have long been concerned with observing Earth's atmosphere from space and with operating in a cold, hostile environment in the Canadian Arctic. There are several specialized areas where current Canadian expertise could be developed into a world-leading ability.

The success of the Phoenix mission paves the way for more comprehensive meteorological measurements on landed missions. Canada should aim to supply a meteorological package on every lander to create to a network of stations on the surface. A method of deploying these packages away from the lander would be advantageous because the vehicle itself modifies the meteorological environment significantly. The wind sensor needs improvement; although the Phoenix sensor was successful, it did not provide data of sufficient quality for a network. A compact unit with no moving parts is required.

The success of the Phoenix lidar and the (non-Canadian) Mars Orbiter Laser Altimeter (MOLA) show the potential for using lidars and similar instruments on the surface and from orbit. The heart of these instruments is the laser: the electro-optic efficiency, lifetime, wavelength and mass of these units is critical to the success and performance of any lidar system. Investment in compact, long-lived and high-efficiency laser sub-systems would pave the way for more capable missions.

Canada has already had success in deploying orbital spectrometers to measure the composition and structure of the Earth's atmosphere (e.g. the SCISAT satellite and the OSIRIS instrument on the Swedish satellite ODIN). Developing similar instruments capable of using several measurement techniques could offer a low-risk, high-value opportunity for Canadian participation in orbiting planetary missions. A SCISAT-style mission to Mars offers the potential for a high science return with a known instrument.

The safe entry of vehicles into the Martian atmosphere, as well as aerobraking and landing, depend on knowing the state of the atmosphere at the time of entry. Canada has significant experience with instruments that can measure winds and temperatures in the middle atmosphere from orbit. The WINDII instrument has demonstrated this capability in Earth orbit. By building an instrument that can provide the dynamical information required for operational support of entry, braking and landing on planetary surfaces, Canada could encourage the development a continuing market for this technology in exploration missions.

Transmitting data from Mars, both from the surface and from orbit, is critical to the success of missions. Continuing improvements in instruments create the need to transmit more information faster. However, there are currently serious technological limitations on both transmission capability of spacecraft (the rate of data transfer) and reception capability (the time available per day on ground stations to receive data). Solving this problem requires the development of better communications systems and more ground stations and increased time on the ground stations. Canada already has expertise in this area from its heavy involvement with satellite communications in Earth orbit.

Testing and characterization of instruments is very important. Large Mars analogue sites are not required, but test facilities that can mimic a range of Martian weather conditions are required, as are facilities to test orbiting instruments. Canada has a ready-made laboratory in its high Arctic and Canadian scientists have considerable experience working in that environment.

Modelling both of the Martian atmosphere and of the instruments to measure that atmosphere is vital. Because the cost of sending an instrument to Mars is so high, the cost of modeling in advance to ensure success is a high-return investment. There is also a need for Canada to invest in data-processing techniques that will enable scientists here to reliably interpret data returned from Mars.

Finally, it must be possible for Canadians to use data from Canadian and international instruments with atmospheric models to provide new insights into the Martian atmosphere. Several university-based models could be expanded to suit this purpose.

Measuring dust and aerosols is essential because they play such a significant role in the Martian atmosphere. Current instruments provide limited information about aerosols in the atmosphere; new instruments are needed to measure the composition and distribution of sizes of these particles.

Studies of the Martian atmosphere have a practical benefit in assisting the landing of spacecraft on the surface. Beyond that, however, this research increases our understanding of the planets in our solar system. The fact that both Mars and Earth have atmospheres means that skills and knowledge acquired in one venue provide insights into the other.

Planetary studies are both academically challenging and very exciting; this provides an incentive for young people to enter the physical sciences and engineering and receive the rigorous training these fields demand. This helps not only the specialized field of

Martian atmospheric studies, but Canadian science and society as a whole when these well-trained people move into industry, government and academia.

3 Planetary Geology & Geophysics

Planetary geology and geophysics (PG&G) is the study of the origin, structure and evolution of the rocky and icy bodies of our solar system. Within the framework of the Global Exploration Strategy, this includes Earth's Moon, Mars and its two moons, asteroids, comets, and the moons of Jupiter and Saturn.

PG&G research includes basic science (like understanding the rates and processes of planetary differentiation into cores, mantles and crusts and changes in these reservoirs caused by volcanism, impact cratering, and landscape erosion by wind, rivers and glaciers) and also encompasses applied studies (such as the search for water-ice and mineral resources for extraction and processing in support of human colonies, and the characterization of planetary dust for engineering designs of rover vehicles).

Members of the PG&G community have diverse backgrounds, including: geologists specializing in field mapping and resource evaluation; geochemists with expertise in chemical analyses and instrument design and geophysicists with skills in numerical and experimental modeling. Most study the Earth as well as other planets, not only to understand properties and processes of extraterrestrial objects that may have terrestrial analogues, but also to design and test instruments for deployment on other worlds.

Canadian geologists and geophysicists are particularly well known for successful planning and execution of field work in remote areas on Earth, not unlike what is needed for missions to explore other planetary bodies.

There are significant overlaps of PG&G with other disciplines including astrobiology, atmospheric science, solar physics and astronomy. Many research studies in PG&G are interdisciplinary and adapt well to the large team approach used for planetary exploration by all space-faring nations.

Summary of Objectives

Moon

- PG-L-1 Map the distribution and age of lunar bedrock.
- PG-L-2 Characterize the physical, chemical and mineral properties of surface rock, soil and dust.
- PG-L-3 Determine the nature and extent of water and hydrogen at the north and south poles.
- PG-L-4 Estimate the rates, processes and effects of impact cratering.
- PG-L-5 Improve geophysical data on the properties and structure of the lunar interior.

Mars

- PG-M-1 Understand the hydrology and hydrogeology of present and ancient Mars.
- PG-M-2 Characterize the mineralogy and geochemistry of the Martian crust.
- PG-M-3 Improve geophysical measurements on the interior structure of Mars.

Small Bodies and Outer Planet Moons

- PG-S-1 Detailed investigations of the geology, mineralogy and chemistry, gravity and magnetism of asteroids and comets.
- PG-S-2 Describe and model the water ice dynamics of Ganymede, Europa and Enceladus.

The Moon

Objective PG-L-1: Map the distribution and age of lunar bedrock.

A fundamental question in geology is whether the outer crusts of planets formed rapidly early in their histories or more gradually over time. The Moon preserves a record of early crust formation that is unaffected by the interactions of large tectonic plates that have operated on Earth and transformed its surface. The Moon therefore serves as a benchmark for understanding the mechanisms that may have been involved in the formation of early crusts on all of the terrestrial planets.

For some period during the first 100 million years of the Moon's existence, its outer half (at least) was entirely molten. A light-coloured mineral, plagioclase feldspar, crystallized from this ocean of magma and floated to the surface, eventually accumulating to form rocks called anorthosites. These white-coloured rocks are preserved today as topographic highlands, particularly on the far side of the Moon.

Later, after the anorthosite crust and dense mantle below it solidified, and for the next billion years or so, the Moon's interior melted again and again. Basaltic lava flows erupted out onto the older surface, particularly into basins formed by large meteorite impacts, forming dark-coloured volcanic plains called maria. The layered sequence of lava flows, piled one on top of another, preserves a record of the composition and mineralogy of the domains in the Moon's mantle that melted over time.

Further study of the age and composition of both early highland (and later mare) rocks is needed to determine the rate at which the magma ocean solidified, and how its composition and that of the later solidified mantle varied with time and location. This research requires knowing the distribution of bedrock at the surface and then sampling key locations for analysis, either remotely on the Moon or in Earth-based laboratories. Existing lunar rocks available for study were not sampled directly from bedrock (Apollo samples) or are from unknown locations on the lunar surface (lunar meteorites).

Investigations

1. Use remote-sensing data for the Moon (multispectral imaging, radar, gravity, magnetic), including those from the Apollo era and the most recent spacecraft images, as well as Earth-based radar, with Geographic Information System (GIS) techniques for mapping of bedrock.
2. Develop an integrated system of Light Detection and Ranging (lidar) remote-sensing and imaging spectroscopy on landers and rovers to characterize the mineralogy and physical properties of bedrock and define sampling/drilling targets for further geochemical analyses or sample returns.
3. Conduct geochemical and mineralogical analysis of lunar materials in order to refine our knowledge of the diversity of lunar rock types.
4. Measure isotopes of uranium and lead, formed by radioactive decay, in minerals such as zircon and baddeleyite from Apollo samples, lunar meteorites and future sample returns to determine the absolute ages of lunar magmatism.

Objective PG-L-2: Characterize the physical, chemical and mineral properties of lunar surface rocks, soil and dust.

Lunar bedrock is covered by surface rocks called regolith, consisting of rock and mineral fragments, soil and dust formed by repeated impacts by meteorites. It constitutes the principal and most readily accessible resource of raw materials on the Moon available for construction, life support and fuel to support human exploration.

Even after the Apollo missions, the depth and extent of layering of the lunar regolith remain poorly known. The mineral ilmenite (iron-titanium oxide), which is unevenly distributed in the regolith, is of particular interest. This mineral is a potential source of oxygen when heated in a vacuum. It might also be used as a semiconductor and for photovoltaic cells to provide electricity. Defining locations with its richest concentrations will be necessary for human settlement of the Moon.

Lunar dust is the very finest fraction of particles in the regolith. When lofted from the surface, it attaches readily to surfaces by electrostatic charging, thereby causing a myriad of adverse effects—for both astronauts and instruments. For instance, during Apollo missions, dust degraded seals on spacesuits and reduced traction of lunar rovers. To mitigate these effects, the properties of the lunar dust need to be better understood.

Investigations

1. Imaging and spectroscopic analysis to map the distribution of key lunar resources in the regolith, such as ilmenite, both from orbit and on the surface.

2. Characterization of the physical, chemical and mineralogical properties of lunar regolith and lofted dust using a variety of geochemical and geophysical measurements from lander or rover platforms.
3. Systematic analysis of Apollo soils and Earth materials similar to lunar soils using a range of laboratory micro-analytical geochemical techniques in Earth-based laboratories.

Objective PG-L-3: Determine the nature and extent of polar water and hydrogen.

Water will be essential for human settlement of the Moon. It may be synthesized (with considerable effort) from the hydrogen and oxygen presumed to be present in the lunar regolith, but could already exist as ground ice, and recovered much more easily.

Ground ice, if present, is most likely to be found in areas at the south and north poles that lie in permanent shadow from the Sun. These regions, mostly on the floors and lower interior walls of impact craters, are so cold (below minus 230 degrees Celsius) that water and hydrogen delivered to the Moon by impacts from comets and asteroids over its long history could not escape back to space.

Besides its practical value for life support, water preserved at the lunar poles would also have immense scientific value. If the relative ages of different ground ice deposits could be determined, they may preserve changes in the composition and source of meteorites that collided with the Moon over billions of years.

The nature and extent of lunar ground ice is unknown. The *Clementine* and *Lunar Prospector* orbital missions found circumstantial evidence for ground ice at the lunar south pole, but radar imaging from Earth-based telescopes suggests that the ice deposits (if present at all) only form scattered crystals in the lunar regolith. It will be essential to map and characterize the geology of regions suspected of preserving ground ice; determine the water content, chemistry and mineralogy of the regolith and understand its thermal history.

Investigations

1. Initial geological mapping by remote sensing from spacecraft.
2. Ground ice detection from rovers using electromagnetic conductivity and ground-penetrating radar methods.
3. *In situ* sampling and mass spectrometric analyses from rovers to determine the abundance and distribution of water and hydrogen.
4. Testing ground-ice detection and mapping methods in lunar analogue settings on Earth.

Objective PG-L-4: Estimate the rates, processes and effects of lunar impact cratering.

Craters form on the solid surfaces of all planetary objects when they collide with pieces of asteroids or comets, producing large explosions called impacts. Impact cratering is considered to be *the* most important surface process on the Moon because its crust has not been reprocessed by plate tectonics as on Earth, and by erosion of the landscape by water, ice and wind as on Earth and Mars.

By understanding the rates, processes and effects of impact cratering on the Moon, where the record is most clearly preserved, scientists can better understand cratering on all planetary bodies. This is important for a variety of reasons. On the Moon, Mars, Venus, Mercury and the asteroids, the numbers of craters preserved on exposed rock units is the primary means by which their relative ages are determined. In addition, ejection of shocked rocks from impact craters provides a natural method of sampling deeper levels of planetary crusts, avoiding the need for costly deep drilling.

On Earth, impact-cratering processes have concentrated huge resources of metals, such as nickel, at the impact structure in Sudbury, Ontario. It is possible that significant mineral deposits also have been formed at lunar craters.

Investigations

1. Radioactive isotope studies of impact melt glasses and minerals in lunar meteorites and returned Apollo samples to determine the absolute ages and rates of impact bombardment for the Moon (and by extension, for the entire inner solar system).
2. Comparative studies and calibration of pressure and temperature in shocked lunar materials and terrestrial analogues such as from the Mistastin (Labrador) and Manicouagan (Québec) craters, using mineralogical characterization and experimental simulations.
3. Analogue field missions to terrestrial impact craters with well preserved ejecta blankets, such as at the Ries crater (Germany), to understand the depth of origin of ejected materials as a function of crater size, target rock composition and impact angle, combined with a systematic survey of lunar ejecta deposits.

Objective PG-L-5: Improve geophysical data on the properties and structure of the lunar interior.

Despite a wealth of data from the Apollo missions, many geophysical properties of the Moon remain poorly defined and understood. The characterization and interpretation of lunar crustal magnetism is a major, unsolved scientific problem for which there are multiple competing models.

Global mapping of the Moon’s gravity field, particularly over the far side, is incomplete. The size and composition of the lunar core are not known precisely. Absolute thicknesses and volumes of the crust were not determined precisely by seismic measurements made by the Apollo missions.

New geophysical investigations will provide information on the lunar interior and the processes that led to its formation. They will also help quantify the distribution of vital resources (ilmenite, polar volatiles) and natural hazards (moonquakes, radiation from cosmic rays) critical for planning human exploration and settlement of the Moon.

Investigations

1. Measurements of the ancient magnetism of the crust by satellite from low-altitude lunar orbits, and of lunar bedrock samples returned to Earth-based laboratories for more precise measurements.
2. *In situ* measurements of heat flow, seismics, gravity, and magnetics to place limits on lunar interior structure and thermal history.
3. Studies of crustal and upper mantle electrical conductivity to shed light on composition, in particular the presence of water and gases.
4. Seismic network measurements to investigate moonquakes, made simultaneously at least four stations for a period of at least six years, which is the cycle of the Sun’s and Earth’s gravitational forces on the Moon that drive deep moonquakes.
5. Passive seismic array deployments facilitated by use of mobile platforms over large distances (hundreds of kilometres) to provide imaging of the base of the lunar crust.

Mars

Objective PG-M-1: Understand the hydrology and hydrogeology of present and ancient Mars.

If life ever arose on Mars, water was almost certainly an essential ingredient in its genesis and development. Understanding the distribution and form (liquid, solid, gas) of water on Mars throughout its geological history is therefore of considerable significance.

Mars’ climate is currently quite cold and dry. Globally, air temperatures rarely exceed 0 degrees Celsius and are typically minus 60 degrees Celsius. It is even colder near the Martian poles during the long polar nights.

Water on Mars is currently present in various amounts as ground ice in the permanently frozen subsurface. But certain deposits and landforms on the surface of Mars appear to have been formed by rivers or glaciers, suggesting that liquid water was once present, not only in its very early history, but possibly in its recent history as well. The presence of liquid water suggests that the climate of Mars might have been warmer during these periods

Just like on Earth, the long-term changes in the Martian climate are caused by periodic changes in the orbital properties of the planet as it revolves around the Sun. These are recorded by variations in certain properties of water ice formed over time, such as its proportions of isotopes of oxygen and hydrogen.

Future research is needed to improve the detection of subsurface bodies of water ice, in both the Martian polar ice caps and permanently frozen regolith. These bodies of water ice not only provide an *in situ* resource to support human exploration, but may also contain evidence of ancient microbial life. With a proper understanding of the geological context and hydrological cycle, the detailed long-term climate record of Mars could be reconstructed by analyses of isotopes of oxygen and hydrogen in drill-core samples taken from the polar ice caps and ground ice reservoirs.

Investigations

1. Remote detection of subsurface ice via orbiting satellites using radar technologies with improved resolution
2. Direct detection of water ice by landed missions using geophysical and geochemical instruments
3. Detection of evidence of microbial life in ancient permafrost/ground ice
4. Testing of mission-ready drilling technologies at terrestrial analogue sites to determine ice distribution and to collect drill core samples for analysis.

Objective PG-M-2: Characterize the mineralogy and geochemistry of the Martian crust.

The crust of Mars is of tremendous interest to Canadian geologists for two reasons. First, it is very old compared to the surface of Earth, which has been processed extensively by plate tectonics. More than half of the Martian surface is older than 2 or 3 billion years old, and rocks dating to the age of the formation of Mars 4.5 billion years ago, are likely to be preserved. As a result, with ongoing study by remote sensing, *in situ* measurements and ultimately sample returns to Earth for analysis, geologists will be able to unravel exactly how the earliest crust of Mars formed and evolved—a problem that still remains unsolved for Earth.

The second reason for interest in Mars' crust is that, although most of the surface of Mars consists of little-altered bedrocks, a number of secondary minerals have been identified at a variety of locations. Along with photographic evidence for sediments thought to have been deposited by flowing water, these secondary minerals are testament that warmer, wetter periods existed during Mars' early history and may have harboured life.

Fossil organic compounds and other indirect physical, chemical and isotopic evidence of biological activity (referred to as "biosignatures") will be mostly likely found in geological environments where secondary mineralization is most well preserved. Geological data will be essential for identifying these locations.

Investigations

1. Direct surface mapping of primary and secondary mineralogy by imaging and spectroscopic analysis.
2. Subsurface exploration of bedrock using drilling in combination with spectrometry.
3. Searching for biologically-generated atmospheric trace gases (i.e. methane) and their surface or subsurface sources.
4. Direct assessment of the composition of Mars' surface rocks via landers and rovers.
5. Assessing the potential for life at Mars-like sites on Earth, particularly where heated water has circulated through rocks (such as at meteorite impact craters and acid hot springs).
6. Enhancing technology-readiness levels of Mars-destined instruments and infrastructure through testing and deployment at Mars analogue sites on Earth.
7. Developing and testing a Mars sample return strategy that focuses on understanding the origin of the crust, climate change and the search for life.

Objective PG-M-3: Improve geophysical measurements on the interior structure of Mars

Beneath its crust, Mars consists of an iron-rich core surrounded by a thick mantle of dense silicate rocks. Researchers need better estimates of the size, composition and history of temperature changes in the Martian core and mantle. The information will address the origin of large-scale features of the crust, the history of the magnetic field and the effects of both on atmosphere and climate.

The Martian crust is thick, mountainous and heavily cratered in the south, and thin with flat volcanic plains in the north. A remarkable volcanic bulge about the size of North America rises some 10 kilometres above the lowlands in the Tharsis region. Volcanism associated with the northern lowlands and Tharsis would have released significant amounts of water and other gases (including possibly carbon dioxide) into the atmosphere, altering environments for life.

The volcanism was likely caused by changes in the patterns and rates of convection in the Martian mantle, and mechanisms of heat loss from the core. These processes can be addressed through studies on the behaviour of seismic waves through Mars, and experimental simulations and calculations of the stability and properties of rocks and minerals under the very high pressures that exist in the Martian interior.

Planetary magnetic fields are produced from electrical currents generated by convection of iron-rich liquids in the core (the dynamo). A strong magnetic field deflects the solar wind, a stream of charged particles ejected from the sun; this is what protects Earth's atmosphere and surface from the solar wind.

For unknown reasons, the dynamo on Mars ceased to operate and the field is no longer produced. Consequently, the Martian atmosphere, unprotected by a strong magnetic field, was likely stripped away by the solar wind, leaving Mars less hospitable to life. Even today, the solar wind would be a hazard to astronauts working on the planet.

However, relic magnetic fields produced from crustal rocks formed before the loss of the dynamo could provide protection at specific locations. Characterizing the magnetic field in some detail at such places will be an essential precursor to human exploration and settlement of Mars.

Investigations

1. Characterize the composition and mineralogy of the deep interior of Mars, using a mobile network of at least three seismometers, along with models for the distribution of minerals that are stable in the Martian interior.
2. Determine the detailed structure and composition of the Martian crust at local scales for landing site selection and detect the presence of mineral resources using a combination of *in situ* ground-based measurements and data collected from a low-flying plane or balloon.
3. Theoretical and experimental studies of heat transfer in the mantle and core that could explain the origin of the Tharsis volcanic province and the dichotomy of mountainous terrain in the southern half of the planet and flat plains in the north.
4. Collect magnetic data at the lowest possible altitude over extremely strong crustal magnetic fields in areas of the southern hemisphere where people and equipment may be protected from the harmful effects of the solar wind.
5. High-resolution magnetic measurements to characterize the relatively weakly magnetized northern hemisphere and large impact craters.

Small Bodies and Outer Planet Moons

Objective PG-S-1: Detailed investigations of the geology, mineralogy and chemistry, gravity and magnetism of asteroids and comets.

Asteroids and comets are left-over fragments of the building-block materials that accumulated to form the rocky and gaseous planets of the solar system. Knowing their compositions would provide a unique window into the earliest moments of our solar system, and help researchers understand subsequent physical and chemical processes that occurred on the planets.

Pieces of asteroids sometimes reach Earth as meteorites and can be studied in Earth-based laboratories. Meteorite study is the cheapest and lowest risk sampling strategy for asteroids. But direct study is required to gain an understanding of the full variety and characteristics of these small bodies.

Near-Earth objects are asteroids (and a few comets) that have orbits that periodically bring them close to the Earth, and offer the best opportunity for study by orbiters, penetrators (small, light self-contained instrumented spacecraft that impact a surface at high speed) or landers. Because of their low gravity and proximity to Earth, they are potentially cost-effective sources of raw materials (such as metals and water) that could fuel and supply more advanced missions to the Moon and Mars.

Mars' two small moons, Phobos and Deimos, which are thought to be captured asteroids, could be studied in conjunction with investigations of Mars and act as a useful low-orbit staging base for operations on Mars.

There is a need for detailed characterization of the geology, topography, mass, volume, internal density distribution, composition, mineralogy, near-surface regolith water content and geophysical properties of these objects to understand their origin and evaluate their resource potential.

Investigations

1. Remotely sensed properties of near-Earth objects (e.g. imaging, spectral properties, magnetism, gravity).
2. Surface investigation of near-Earth objects (e.g. landers/penetrators engaged in measuring physical properties; on-site geological and mineralogical investigation; and sample returns).

Objective PG-S-2: Describe and model the water-ice dynamics of Ganymede, Europa and Enceladus.

Two of the Galilean moons of Jupiter, Ganymede and Europa, and one of Saturn's satellites, tiny Enceladeus, consist of relatively smooth, water-ice surface shells underlain by buried water oceans. These moons are prime locations for the search of extraterrestrial life, complementing studies of Mars and the largest moon of Saturn, Titan, which possesses a thick nitrogen atmosphere and liquid hydrocarbon lakes.

In 2005, the *Cassini* spacecraft discovered remarkable water-rich plumes venting from the south polar region of Enceladeus, similar to geysers on Earth.

Research is needed to delineate the nature and size of the subsurface water oceans on these moons, and to understand why and how their surfaces are resurfaced by water eruptions.

Investigations

1. Application of ice-penetrating radar to map water distribution within and potentially beneath icy shells.
2. Ice tectonics studies of the resurfacing processes on icy moons, built from models of continental ice-sheet formation and dynamics on Earth.
3. Developing and testing remote-sensing technologies at terrestrial analogues sites such as the sulfur-rich springs which discharge on to the surface of glacial ice at Borup Fiord in Canada's high Arctic.

Roadmap

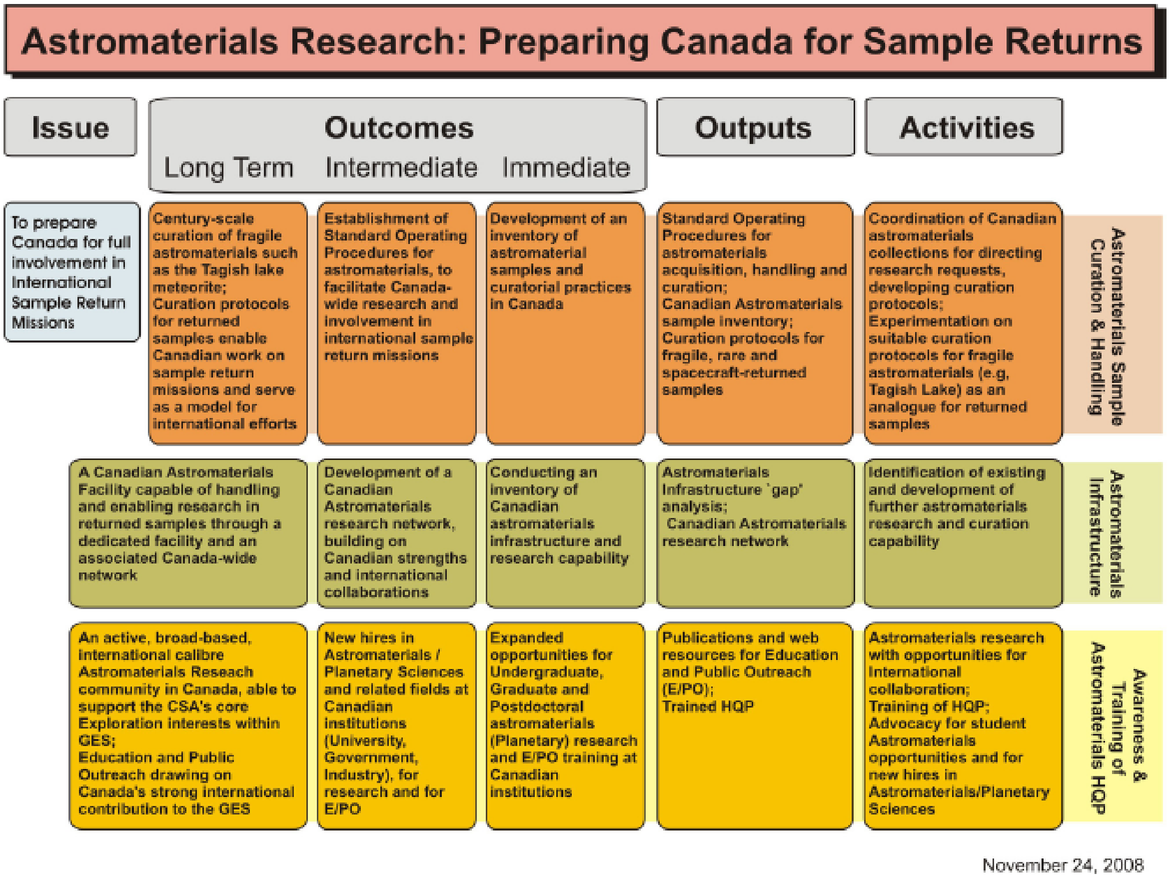
The Canadian PG&G community is small compared to the Canadian Earth Sciences community, but has well recognized expertise in particular areas (like analogue field studies; impact cratering; remote sensing; hydrogeology; meteorite mineralogy; *in situ* microanalysis; geochronology and isotope geochemistry; field geophysics and numerical modeling).

This expertise will be become more developed with opportunities for Canadian geologists and geophysicists (including students) to participate in planetary mission teams that support the Global Exploration Strategy.

National groups and associations can play an important role in bringing Canadian expertise in PG&G to the attention of mission planners both in Canada and abroad. Examples of such groups are the recently established Canadian Lunar Research Network and the Planetary Division of the Geological Association of Canada.

It will also be important to create national facilities focused on key research methodologies that support the science goals of PG&G. Examples include facilities for the curation and analysis of samples to be returned from the Moon, Mars and asteroids, and for developing and testing portable field instruments for *in situ* geochemical and geophysical measurements.

An Astromaterials Discipline Working Group (ADWG) met under contract to the CSA from 2007 to 2009 to consider carefully the means by which Canada and Canadian scientists can begin to prepare now for future sample returns from space missions. ADWG members consider astromaterials research to be infrastructure-critical and not mission specific (i.e. it supports all of the above multi-year, multi-mission space exploration investigations involving planetary geology and geophysics). This working group has identified how to build Canada's capacity in astromaterials research through sample curation and handling; infrastructure analysis and improvements; training of highly qualified personnel and public awareness). They have proposed immediate activities to make this happen, and have considered the risks involved with both implementing and not implementing these plans. The ADWG presented their ideas in a summary White Paper (available on request) and in the logic model found below:



Astromaterials Research: Preparing Canada for Sample Returns

Issue	Outcomes			Outputs	Activities	
	Long Term	Intermediate	Immediate			
To prepare Canada for full involvement in International Sample Return Missions	Century-scale curation of fragile astromaterials such as the Tagish lake meteorite; Curation protocols for returned samples enable Canadian work on sample return missions and serve as a model for international efforts	Establishment of Standard Operating Procedures for astromaterials, to facilitate Canada-wide research and involvement in international sample return missions	Development of an inventory of astromaterial samples and curatorial practices in Canada	Standard Operating Procedures for astromaterials acquisition, handling and curation; Canadian Astromaterials sample inventory; Curation protocols for fragile, rare and spacecraft-returned samples	Coordination of Canadian astromaterials collections for directing research requests, developing curation protocols; Experimentation on suitable curation protocols for fragile astromaterials (e.g, Tagish Lake) as an analogue for returned samples	Astromaterials Sample Curation & Handling
	A Canadian Astromaterials Facility capable of handling and enabling research in returned samples through a dedicated facility and an associated Canada-wide network	Development of a Canadian Astromaterials research network, building on Canadian strengths and international collaborations	Conducting an inventory of Canadian astromaterials infrastructure and research capability	Astromaterials Infrastructure `gap' analysis; Canadian Astromaterials research network	Identification of existing and development of further astromaterials research and curation capability	Astromaterials Infrastructure
	An active, broad-based, international calibre Astromaterials Reseach community in Canada, able to support the CSA's core Exploration interests within GES; Education and Public Outreach drawing on Canada's strong international contribution to the GES	New hires in Astromaterials / Planetary Sciences and related fields at Canadian institutions (University, Government, Industry), for research and for E/PO	Expanded opportunities for Undergraduate, Graduate and Postdoctoral astromaterials (Planetary) research and E/PO training at Canadian institutions	Publications and web resources for Education and Public Outreach (E/PO); Trained HQP	Astromaterials research with opportunities for International collaboration; Training of HQP; Advocacy for student Astromaterials opportunities and for new hires in Astromaterials/Planetary Sciences	Awareness & Training of Astromaterials HQP

November 24, 2008

4 Solar-Terrestrial Science

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 harsh conditions of space neccessitate a better understanding of the environment through solar terrestrial science in order to enable Global Space Exploration, which can itself provide opportunities for further study of the space enviroment.

The overarching goal of solar-terrestrial science is to advance knowledge of the *fundamental physics of and connections between* the Sun and other bodies in the solar system, and to improve our ability to forecast and mitigate the resulting effects on society.

The Global Exploration Strategy (GES) will provide unique opportunities for high-priority solar-terrestrial studies of nearby planetary bodies (such as the study of plasma physical processes in the near-planet space environment and their effects on space exploration). Equally important, GES will provide opportunities for studies *from* these bodies (e.g. a lunar observatory for solar or near-Earth space (geo-space) studies).

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 solar-terrestrial observatory for solar, Earth and near-Earth (geo-space) 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 both cases, solar-terrestrial science 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.

Summary of Objectives

- ST-L-1 Lunar plasma environment and regions
- ST-L-2 Orbiting lunar solar-terrestrial observatory
- ST-L-3 Space radiation – forecast and mitigation
- ST-M-1 Mars magnetic field
- ST-M-2 Solar wind bombardment of the Mars upper atmosphere
- ST-M-3 Space weather on Mars

Objectives and Investigations

Objective ST-L-1: Lunar plasma environment and regions

The near-Moon electromagnetic and plasma environment play 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 ultraviolet light, which results in the emission of photo-electrons 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 1 is an artist's concept of the plasma environment on the Moon, including its different plasma regions and interactions with the solar wind.

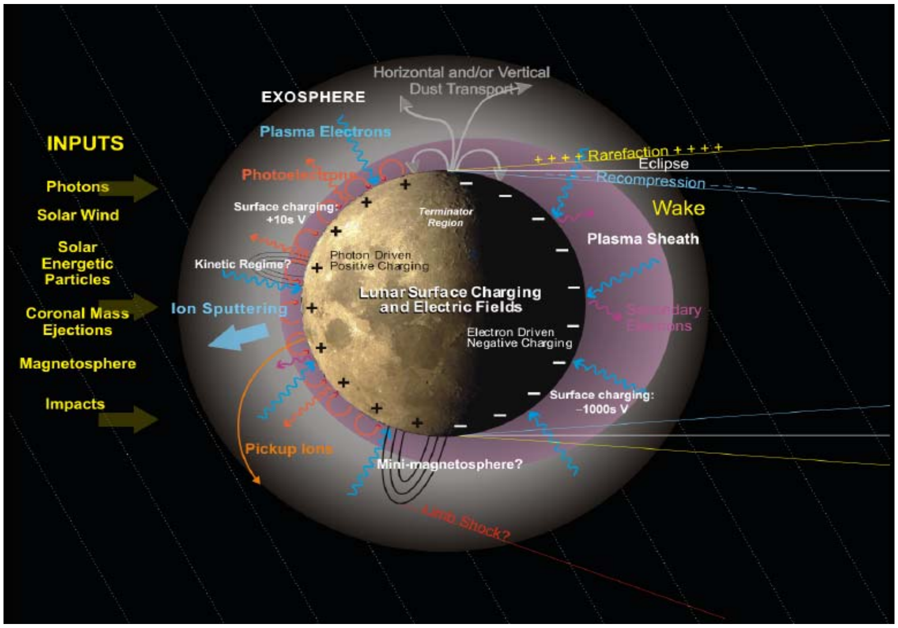


Figure 1 Plasma environment and regions on the Moon and interactions with the solar wind (Delory et al., 2008 / UC Berkeley)

Investigations:

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 kilometres 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.

2. 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.

3. 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.

4. 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 kilometres 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.

5. 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 behaviour 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.

Objective ST-L-2: Orbiting lunar solar terrestrial observatory

The concept of using the Moon as an orbiting observatory for near-Earth space imaging and for studying the physics of the solar system (heliophysics) was first proposed by the Canadian solar-terrestrial 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.

Investigations:

1. 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).
2. Imaging of the geo-corona and the aurora: Global imaging of the geo-corona (the solar, far-ultraviolet light reflected off the layer of neutral atoms at the top of the Earth’s upper atmosphere) is an extremely powerful technique for monitoring the dynamics of different atmospheric constituents in the upper atmosphere. Likewise, imaging the Northern

Lights (aurora) enables us to continuously monitor the global dynamics of the Earth's magnetic field. This is an important and cost-effective tool for monitoring and characterizing space weather in real-time on a global scale.

3. Remote sensing of Earth atmospheric processes: Studying large-scale albedo (the surface reflectivity of the Sun's radiation), clouds, atmospheric lightning, airglow (the weak light emission from the Earth's atmosphere) and upper atmospheric winds will be essential to advancing our understanding of how the different processes in the Earth's atmosphere and upper atmosphere interact.

4. Coronal mass ejection: A coronal mass ejection (CME) is an ejection of energetic plasma from the Sun at speeds up to 10 million kilometres an hour. When a CME reaches the Earth, it can disrupt radio transmissions, cause power outages (blackouts), disable communications satellites or cause satellite navigation systems to malfunction.

Objective ST-L-3: Space radiation - forecast and mitigation

Even at 9100 metres (30 000 feet) 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. Solar-terrestrial science will provide the knowledge base for developing protection measures and mitigation strategies against space radiation and other harmful effects of the space environment.

Investigations:

1. Real-time monitoring and forecast of near-Earth space conditions affecting astronauts on and en route to the Moon (i.e. space situation awareness).
2. Monitoring and real-time broadcast of radiation bombardment events on the lunar surface.
3. Development of magnetic shields to protect against radiation.

Objective ST-M-1: Mars magnetic field

Mars is just as inviting as the Moon for solar-terrestrial research. The Mars Global Surveyor mission recently confirmed the very weak or 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 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.

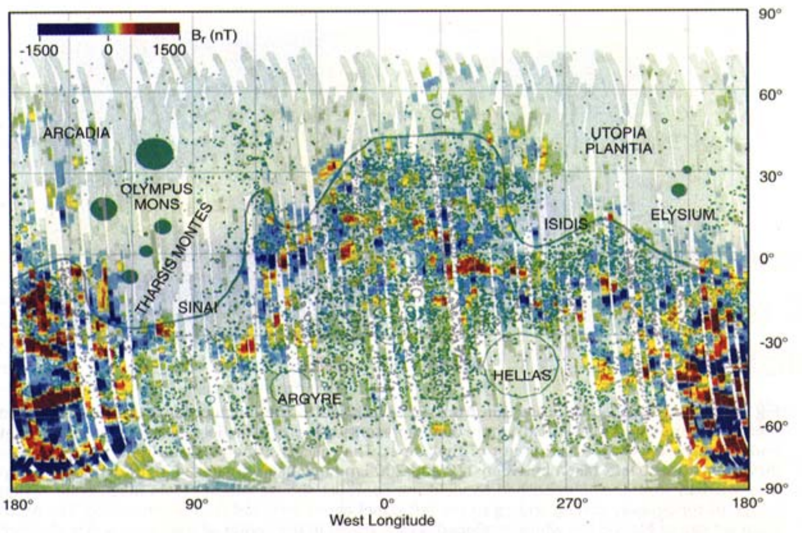


Figure 2 Map of crustal magnetic field anomalies on Mars, overlaid with the large craters and the north-south dichotomy boundary, with the magnetic field strength color-coded, (Acuna et al, Global Distribution of Crustal Magnetization Discovered by the Mars Global Surveyor MAG/ER Experiment, 1999).
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Investigations:

1. 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 researchers 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.

Objective ST-M-2: Solar wind bombardment of the Mars upper atmosphere

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.

Investigations:

1. 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.

2. 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.

Objective ST-M-3: Space weather on Mars

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.

Investigations:

1. 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.

5 Space Astronomy

Space provides an ideal environment for astronomy. On Earth, atmospheric turbulence limits the resolution and sensitivity of ground-based telescopes, particularly in the visible region of the electromagnetic spectrum. In addition, the atmosphere strongly absorbs light at ultraviolet and most infrared wavelengths, blocking much of the spectrum. Emission of light by atoms and molecules in the upper atmosphere is a dominant source of noise, greatly reducing the sensitivity, particularly at infrared wavelengths.

These limitations motivated development of the highly-successful Hubble Space Telescope (HST) and its successor, the James Webb Space Telescope (JWST), scheduled for launch in 2014.

Due to the wave nature of light, the resolution of a telescope is proportional to the diameter of its aperture, normally the telescope’s primary mirror. The light-collecting area increases as the square of this diameter, and for observations of faint point-like sources, the sensitivity increases in proportion to the fourth power, providing enormous scientific potential for large-aperture telescopes.

Cost and technological issues have so far limited the size of space telescopes. HST has a 2.4-metre primary mirror. JWST will have a 6.5-metre mirror. In contrast, the largest telescopes on Earth have apertures in the range of 8 to 10 metres. A new generation of 30- to 40-metre telescopes is planned.

The Moon provides a unique opportunity to overcome many of the limitations that affect telescopes on Earth, and some of those that limit the size of space telescopes. Because the Moon effectively has no atmosphere, the performance of a lunar telescope would be similar to that of a space telescope of equal aperture.

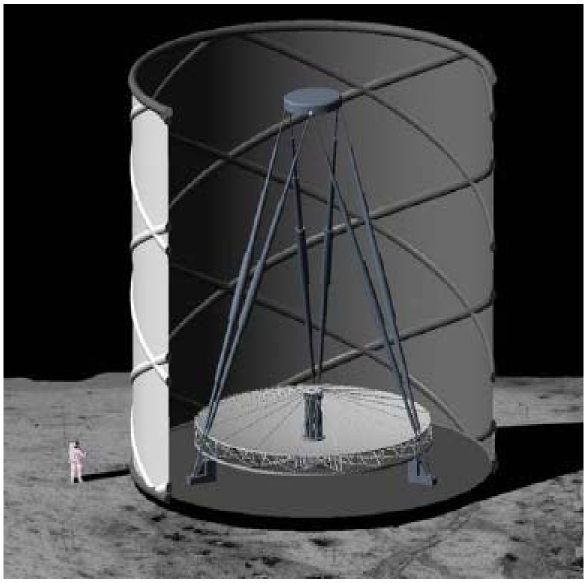

Figure 2.4.1. Artist's concept of a large lunar telescope. (T. Connors, Univ. of Arizona)

The Moon has several other advantages: it would provide long-term stability as a platform for telescopes, and there could be infrastructure support associated with new lunar missions envisaged in the Global Exploration Strategy being developed by international space agencies.

Furthermore, the one-sixth gravity of the Moon offers the potential for new technologies that may allow large-aperture optical/infrared lunar telescopes to be built at a lower cost than free-flying or orbiting space telescopes. The Moon may also offer advantages for astronomy at other wavelengths. For example, a radio telescope located on the far side of the Moon would be free of interference from radio transmissions on Earth.

The sections below highlight several fundamental scientific questions that lunar telescopes can address.

Summary of Objectives

- SA-1 Investigate the nature of dark matter and dark energy.
- SA-2 Investigate when the first stars and galaxies formed and their properties.
- SA-3 Investigate how galaxies evolved and the history of star formation over time.
- SA-4 Investigate how stars and planetary systems form and what determines their physical properties.
- SA-5 Investigate how common Earth-like planets are and the conditions for life on such planets.

Objectives and Investigations

Objective SA-1: Investigate the nature of dark matter and dark energy.

A consistent picture of the history of the Universe has developed in recent decades. Originating spontaneously about 13.6 billion years ago, space expanded rapidly during an initial period of inflation that lasted about 10^{-30} seconds. At the end of inflation, elementary particles were created that eventually became the matter and radiation that we see today. This was the "Big Bang."

After this, the Universe continued to expand and cool, but at a slower rate, becoming transparent to light about 400 000 years later. (Figure 2.4.2).

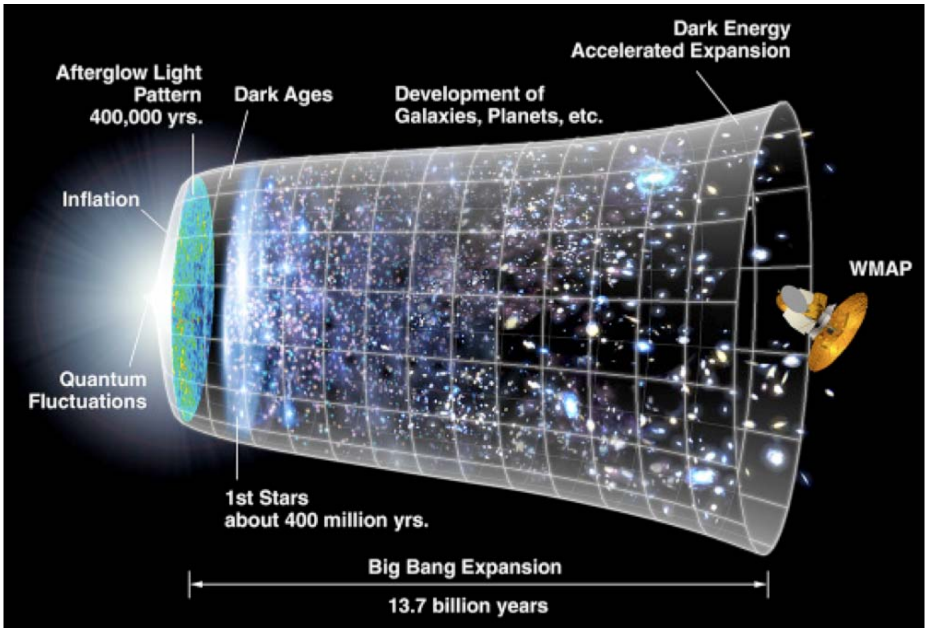

Figure 2.4.2. History of the Universe (NASA: WMAP team).

The primordial gas produced by the Big Bang soon began to clump under its own gravity, forming hot luminous objects that were the first stars. These, and subsequent generations of stars, produced heavier elements through nuclear reactions within their cores, and spread them throughout space during supernova explosions. These elements became the constituent material of planets like Earth.

One of the most remarkable recent discoveries is that the stars, planets and the diffuse gas that constitutes all visible matter in the Universe make up only a small fraction of its total mass. This ordinary (baryonic) matter contributes about 4% of the total mass-energy density of the Universe (Figure 2.4.3). Much more mass, 22% of the total, is a new form of matter not yet seen on Earth. This dark matter emits no light, but its presence is inferred from its gravitational influence on the motions of stars and galaxies.

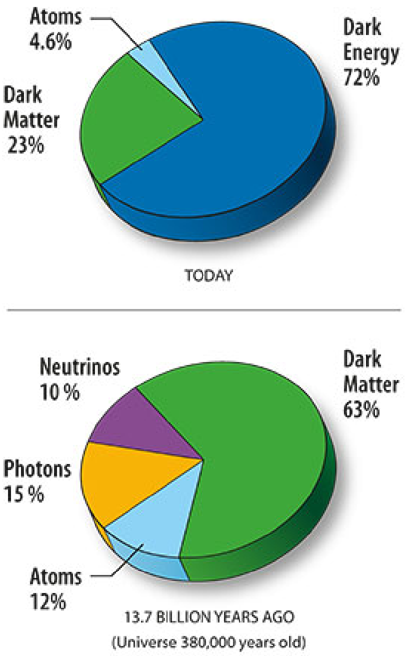

Figure 2.4.3. Composition of the Universe (NASA/ WMAP science team).

Even more surprising is strong evidence that fully 74% of the total consists of a new form of matter with very unusual properties. Normal matter and energy generates a gravitational force that always attracts. However this new matter, called dark energy, generates a gravitational force that repulses. Dark energy pervades the Universe; its presence is causing the Universe to expand at an ever-increasing rate.

Learning more about the nature of dark matter and dark energy can best be accomplished by putting new telescopes in space or on the Moon.

Investigations:

1. Studying distant galaxies: The nature of dark matter can be investigated by studying distant galaxies. Light emitted by stars in these galaxies is deflected by the gravitational potential of dark matter clumps as it travels towards us. This results in small distortions of the apparent shapes of the galaxies (Figure 2.4.4).

Through a statistical analysis of millions of galaxies, scientists can determine the degree of clumping of the dark matter, which provides important clues to its nature. This type of observation requires a telescope with a wide field of view and excellent image quality, and is best done with telescopes in space or on the Moon.

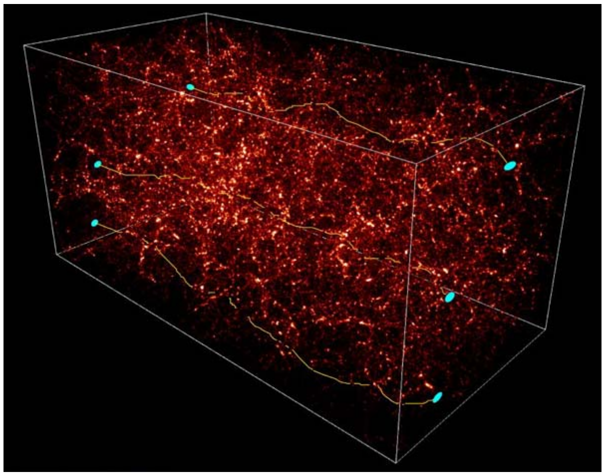

Figure 2.4.4. Gravitational lensing, by dark matter fluctuations (orange), shears the images of distant galaxies (blue circles), increasing their ellipticity (S. Columbi, IAP).

2. Studying the expansion of the Universe: Dark energy can be studied through its effect on the expansion of the Universe. The expansion causes an increase in the wavelength of light propagating through the Universe, which is known as the redshift. By measuring the redshift as a function of distance to the emitting objects, it is possible to determine the evolution of the expansion rate over cosmic time. This, in turn, is related to the equation of state of the dark energy (i.e. the relationship between its pressure and energy density). Therefore, measurements of redshifts and distances of distant objects can be used to test theories of dark energy.

This type of study, using supernovae (exploding stars) as standard candles, led to the discovery of the acceleration of the Universe. In recent decades, scientists have used telescopes on Earth to determine the redshifts and distances of several hundred supernovae. Extending these measurements to greater distances will provide better discrimination between different dark energy models. This will require the high sensitivity and wide field of a space or lunar telescope.

Objective SA-2: Investigate when the first stars and galaxies formed and their properties.

Several hundred million years after the Big Bang, the primordial gas that filled the Universe cooled sufficiently to undergo gravitational collapse to form the first stars (Figure 2.4.5). These first stars were supermassive, having a hundred or more times the mass of the Sun, and had relatively short lives.

Their prodigious radiation, and the energy released by their explosive deaths, heated the interstellar medium creating expanding bubbles of ionized gas. This, in turn, prevented further star formation because hot gas resists gravitational collapse. Only the most massive clusters of stars had sufficiently strong gravitational attraction to continue to accrete gas and build up a stellar population. These massive collections of stars and gas were the first galaxies.

Investigations:

1. These first galaxies should be detectable by JWST. However, the higher resolution and sensitivity of a 20-metre-class space telescope is needed to reveal the first stars and allow the properties of the first stars and galaxies to be studied in detail.

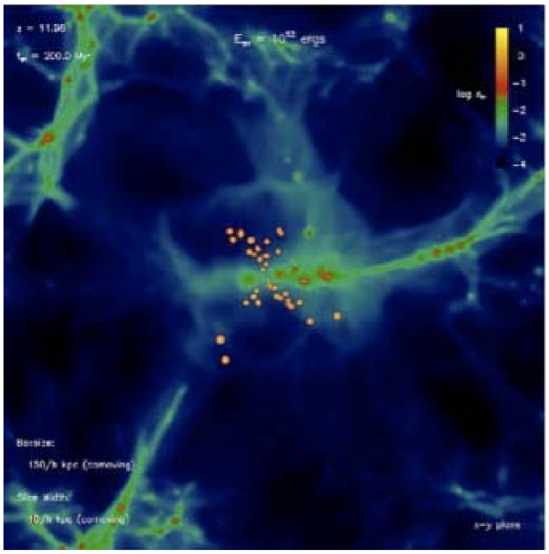

*Figure 2.4.5. Simulation of the formation of the first galaxies, showing gas density 200 Myrs after the formation of the first stars. Orange dots show sites of supernova explosions (Grief et. al, Fi*rst Stars II Conference 2008).

Objective SA-3: Investigate how galaxies evolved and the history of star formation over cosmic time.

As time passed, galaxies grew by accreting their neighbours (Figure 2.4.6). These galaxy mergers compressed the gas, triggering intense star formation. Scientists do not know what processes resulted in the wide range of galaxy types that are seen today. Detailed studies of individual systems at high spatial resolution will help researchers better understand the physics of galaxy formation and evolution.

The primordial gas consisted almost entirely of hydrogen and helium. When and how were the heavier elements formed? These elements are produced in stars and dispersed into the interstellar medium by supernova explosions. Thus, by measuring the rate at which stars were forming over a wide range of cosmic time, one can determine when the bulk of the elements formed.

Investigations:

1. A 20-metre lunar telescope, with a hundred times the sensitivity of the Hubble Space Telescope, will be able to determine the star-formation rate from the present time back to

that of the first galaxies. A decade of observations with the Hubble Space Telescope has shown that the star formation rate was higher in the past, when the Universe was an order of magnitude denser. Lunar telescopes will enable scientists to study the redshifts and luminosities of very faint galaxies, which will help determine the complete history of star formation in the Universe.

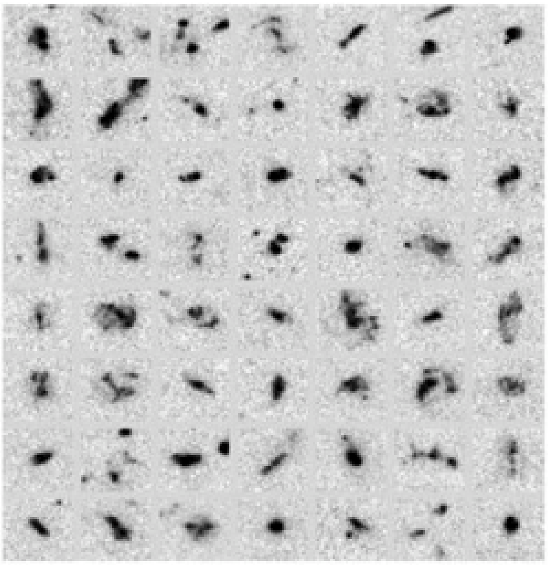

Fig. 2.4.6. Distant galaxies imaged by HST. These are much less regular than the Milky Way, showing patchy star formation and the merging of smaller galaxies (C. Steidel, Caltech).

Objective SA-4: Investigate how stars and planetary systems form and what determines their physical properties.

Stars and planets form when clouds of interstellar gas and dust become unstable and undergo gravitational collapse (Figures 2.4.7 & 2.4.8). The details of this process are not well understood, since they involve a complex interplay of atomic physics, hydrodynamics and the transfer of energy and momentum.

Fundamental questions, such as what determines the mass of a star, when do planetary systems form and what determines the masses and orbits of the planets, do not yet have answers.

Investigations:

1. A large-aperture (20 metres or more) lunar telescope would be able to address questions related to how stars and planetary systems form and what their properties are. Observations that penetrate dense, dusty, molecular clouds are needed to reveal the cores of collapsing stellar systems down to the smallest sizes. This requires infrared observations at high spatial and spectral resolution and high sensitivity.

Ground-based telescopes are limited in this area and, while the James Web Space Telescope can make important advances, its spatial and spectral resolution are limited as well. A lunar telescope would extend observations of protostellar systems to low-mass stars, bridging the gap between stars and planets. Direct observations of protoplanetary discs around young stars will reveal newly forming planets and their relationship with the surrounding gas and dust. This will improve understanding of the physics of planetary formation.

Figure 2.4.7. The Large Magellanic Cloud, a small galaxy orbiting the Milky Way. The reddish concentration on the upper left side is the 80-Doradus star forming region (NASA).

Figure 2.4.8. HST image of the N11B star-forming region in the Large Magellanic Cloud. The young blue stars and dark clouds contain newly-forming stars and planets. (NASA, ESA, and The Hubble Heritage Team (AURA/STScI))

Objective SA-5: Investigate how common Earth-like planets are and the conditions for life on such planets.

Almost 500 extrasolar planetary systems have now been discovered. These planets are all much more massive than Earth, resembling Jupiter or Neptune. But this is a result of the limitations of current telescopes: smaller, less massive, planets are harder to detect. Earth-like, terrestrial planets are expected to be common.

Direct observations of planets is hindered by their close proximity to their host star; seen from comparable distances, the Sun would appear 1010 times brighter than the Earth. Certain techniques have allowed a few large planets to be seen (Figure 2.4.9), but terrestrial planets remain beyond reach, even for the next generation of extremely large, ground-based telescopes.

Investigations:

1. Develop new space- or lunar-based telescopes to find and study Earth-like planets. Because space-based telescopes have no atmosphere to contend with, they can overcome the limitations imposed on Earth-based by this factor. Telescopes such as the Terrestrial Planet Finder, a mission concept currently being studied by NASA, could study Earth-like planets. A comparable telescope located on the Moon would be equally effective.

2. Develop new space- or lunar-based telescopes to study the chemistry of interstellar gas. Some prebiotic organic molecules have already been detected in nearby star-forming regions (Figure 2.4.10). A large space or lunar telescope would enable the detection of more complex molecules and allow scientists to trace the composition and distribution of molecules within individual protoplanetary systems.

3. Direct spectroscopy of terrestrial planets could reveal the presence of biogenic molecules such as oxygen. This would be strong evidence of the presence of life on these planets.

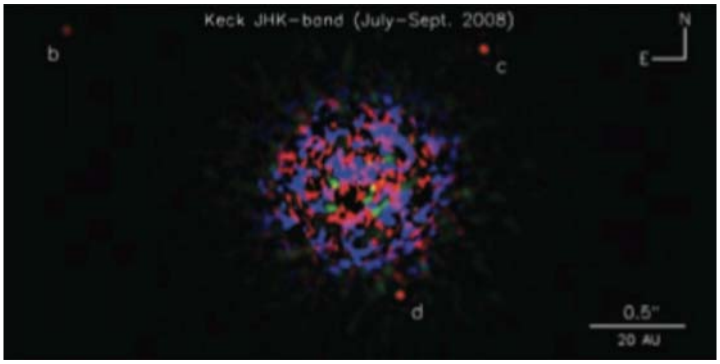

Figure 2.4.9. Three Jovian planets (b, c, d) orbiting the nearby star HR 8799. The large blob at the centre is residual diffracted light from the central star. (Marois et al., Direct imaging of multiple planets orbiting the star HR 8799, 2008),

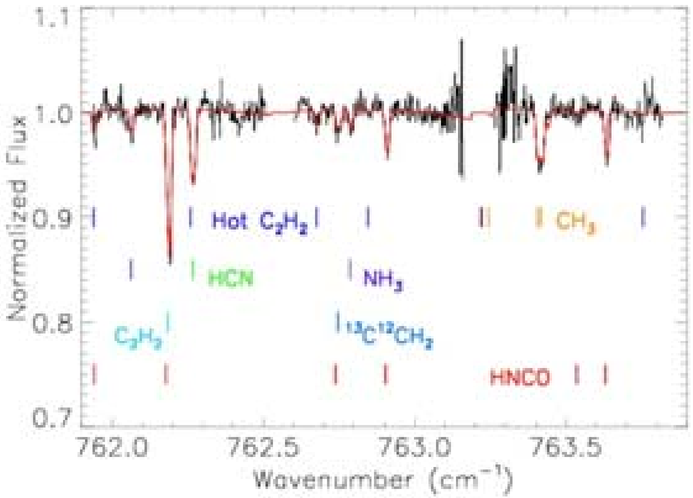

Figure 2.4.10. Infrared spectrum of the massive protostar NGC 7538 IRC 1, showing absorption lines of organic molecules. These and other prebiotic molecules are the precursors of life. (Knez et al., 2005)

6 Advanced Life Support

The purpose of life support is to sustain life on space missions, primarily by providing air, water and food. Future advanced life-support systems will improve current life-support systems already used on space missions.

In most instances, biological life-support systems, which involve the use of biological systems like plants and micro-organisms, are proposed for future long-duration space missions because of their capacity to recycle air, water and food. The better the capacity of a life-support system to recycle crew waste, the less air, water and food the crew must transport with them.

We know that biological life support systems can function because they do so constantly here on Earth. But if we want to use them on future exploration missions, we must determine their suitability for the altered environments in space and on planetary surfaces. For example, these environments typically have lower gravity and atmospheric pressure and higher radiation levels than on Earth—factors that can significantly affect the viability of biological organisms.

Canada began research on space-relevant biological life-support systems in the early 1990s. Since that time, our capabilities have grown tremendously and Canada is now the world leader in biological life-support system research and technology development. The rapid growth of Canadian expertise has been the result of several factors, including: a large and technically sophisticated greenhouse sector that successfully operates under challenging climatic conditions; well planned technology transfer strategies between the academic and industrial sectors and a strong emphasis on international research collaborations.

Recent activities, such as Canada's contribution of the Higher Plant Compartment of the European Space Agency's MELiSSA Pilot Plant and the remote operation of the Arthur C. Clarke Mars Greenhouse in the Canadian high Arctic, demonstrate Canadian capabilities with direct applicability to advanced life-support systems.

There is also a significant latent potential within Canadian institutions and organizations with respect to directly applicable advanced life-support technologies in areas such as: horticultural management strategies for candidate crops; growth media; food processing; water management; atmosphere management; energy management; imaging; waste management; environment sensors; thermal control; lighting systems; robotics; command and data handling; communications systems; structures; *in situ* resource utilization;, space analogues and mission operations.

Space robotics has been a key niche area for Canada for some time. Canada can continue to excel in this field through its application to future space-based biological life-support systems. Canadian institutions also have strong representation in imaging and environment sensors, which are also required for advanced life-support systems.

With regard to future space exploration, the Canadian advanced life-support (ALS) community is focusing on infrastructure for planetary surfaces like the Moon and Mars rather than on microgravity environments, such as low-Earth orbit or spacecraft traveling away from Earth.

We propose several lunar surface elements that will enable Canada to grow the first plants on another planetary body, explore important scientific questions about growing plants in the lunar radiation and gravity environment, and make the first steps toward creating larger-scale plant production systems. This experience would enable Canada to develop a biological life-support system that could provide a portion of the air, food and water that exploration crews would require for survival on planetary surfaces.

It would be difficult to develop these lunar systems without corresponding advancement of relevant technologies on Earth. Canadian institutions have already developed plant-growth chamber infrastructure in collaboration with European universities. The technical readiness of systems for the proposed lunar missions can be improved by enhancing these terrestrial technologies.

Several other Earth-based developments are also needed, including facilities to remotely control ground- and space-based ALS systems, to integrate and test these systems and to train astronauts and ground controllers in their use. These facilities would reduce the technical and financial risks associated with developing systems for planetary surfaces.

Canadian advanced life-support activities have already been successful in terrestrial technology transfer and in developing highly qualified personnel; these will be key outputs of future research into space-based systems. Space-based systems face numerous challenges related to resupply and resource limitations, environmental conditions and limited crew time. Solving these problems will also benefit Earth-based systems, which face many similar challenges. For example, space-based advanced life-support systems will require significant robotic and energy management capabilities and applying these technologies will help Canadian greenhouse operators reduce their two highest input costs, labour and energy.

The space technology “pull” can also help address recent environmental legislation and regulations facing terrestrial growers. In particular, Canadian greenhouse growers must move to water-recirculating technologies or otherwise invest in on-site wastewater treatment systems to comply with recent nutrient-management legislation.

Space-based biological life-support systems will require the ability to recycle most of the human waste streams related to air, water and food systems, such as carbon dioxide, waste water and inedible biomass. Therefore, effective solutions to minimize resource output and waste will be highly transferable to the terrestrial sector.

Additional benefits from the proposed Canadian ALS roadmap include the development of suitable plant production systems for remote/northern communities, improved food security and safety, green buildings, alternative plant pest control and water resource use efficiency.

Advanced life support research also has significant educational potential, as demonstrated by the very successful Tomatosphere project, which distributes tomato seeds exposed to microgravity or a simulated Mars surface environment to thousands of classrooms across Canada.

Goal

Enable sustained human planetary exploration through technological advancements to provide food for the crew, air revitalization and potable water recycling.

The inherent goal of a life-support system is to sustain the life of crews on space missions. To achieve this goal, the Canadian ALS community is focused on developing innovative technologies and applications that will enhance our ability to exploit biological systems for life support by improving system reliability and increasing closure in air, food and water.

We advocate an incremental strategy to advance ALS technology, starting with ground-based activities leading to space-based research.

Summary of Objectives

- ALS-1: Earth-integrated life-support system testbeds
- ALS-2: Lunar Scalable CanALSS

Objectives and Investigations

Objective ALS-1: Earth-integrated life-support system testbeds

1. Growth Chamber Utilization:
This activity will capitalize on current Canadian expertise and infrastructure while enhancing collaborative interactions among the Canadian ALS community. The goal is to make common plant-growth infrastructure available to participating institutions nationwide and internationally, using both existing infrastructure and newly developed systems.

Research at these facilities will focus on:

- food characterization studies to evaluate the quality and production of candidate crops under operational conditions, including variable pressure, atmospheric compositions, lighting source, etc.
- investigating genetic requirements (e.g. low-light tolerance and other environmental stress adaptations, plant architecture, nutritional attributes, etc.).
- innovative technology developments and applications such as recycling protocols, sensors and pathogen control techniques that leave no toxic residues.

Standard operating procedures will be developed for participating institutions allowing for direct-study comparisons.

These studies will benefit from existing research collaborations between the University of Guelph, the University of Gent in Belgium, the University of Bern in Switzerland and the University of Napoli in Italy, which focus on food characterization, and on concurrent plant production trials in the four countries. Additional international partners may become involved in similar studies.

2. Earth Control Facilities

The Canadian ALS community proposes to develop a series of distributed command and control facilities to control ground-based and space-based advanced life-support systems. These control centres will allow the Canadian institutions that possess relevant ALS expertise to monitor and control the proposed infrastructure elements. Existing infrastructure nodes such as the CSA's Payload Telescience and Operations Centre could be used for early elements.

3. Earth-Integrated Life-Support System Test-Bed

This facility would be used to integrate the disparate capabilities required for space-based biological life-support systems. In many instances, these capabilities have been qualified in isolation but not yet integrated with a plant production system.

This facility would enable these capabilities to be tested in unison and thus address integration and interface issues and growth architectures (i.e. optimizing production systems and crop lay-out for controlled environment systems). They would also provide data on overall test-bed operation and thus provide better estimates for lunar growth system sizing and requirements that account for minimal mass and energy allocations.

The proposed facility would be located at an accessible venue (e.g. CSA Headquarters) where Canadian researchers could bring their systems for integrated trials. The potential for terrestrial technology transfer and the development of highly qualified personnel from this facility would be significant.

4. Earth Integrated Training and Simulation Centre

Because ALS systems are designed to support human crews, there is an obvious requirement to ground-test these systems with humans in the loop prior to any space-based mission. The roadmap shown below proposes that a facility be constructed and used to conduct human integrated tests. This facility could be installed at a Canadian Analogue Research Network site with the additional intent to serve the needs of related scientific communities with an interest in space analogue and associated field science, such as operational space medicine, astrobiology and geology.

An Earth-based human integrated training and simulation centre is necessary because it will:

- afford an environment to define realistic system requirements
- provide real metabolic waste streams and system dynamics
- verify life support system outputs and their acceptability for humans
- address integration issues
- address relevant habitability issues (adequacy of facilities, maintainability, crew time).

In addition, this facility would provide unique training for astronauts and ground controllers in operating ALS systems. This work will likely require international partnerships because developing high-fidelity, human-integrated life-support systems requires significant funding and involves challenging safety issues.

Objective ALS-2: Lunar Scalable CanALSS

1. Lunar Plant Growth Lander

The roadmap includes plans for a robotic lander to grow the first plant on another planetary body. This contribution would likely be in the form of a payload contribution to an international partner mission. It would involve a simplified system – Arabidopsis seedlings grown on an agar plate – to demonstrate the feasibility of growth on the lunar surface and improve our understanding of the effects of the lunar environment on plant growth. In particular, this study would employ a remote imaging (fluorescence) system to investigate the effects of lunar radiation on the seedlings.

This near-term mission would help mobilize and develop the Canadian community and important international collaborations.

2. Lunar Salad Machine

A salad machine would represent a transition between a system that is not integrated with the human life-support system and one that is relied upon by the crew for some modest contributions to life support and psychological benefits. In particular, several studies and anecdotal accounts from crews have demonstrated that plants can provide a psychological boost to crews in remote-duty stations and low-Earth orbit missions. In the early stages, especially for lunar missions, the baseline life-support systems will be physico-chemical systems that incorporate non-biological physical and chemical processes to recycle consumables.

A lunar salad machine would provide confidence in biological life-support systems on the Moon. It would also use a growth system incorporating some of the technologies that would later be used to create a scaled-up lunar plant production system. In particular, it would deploy modular components similar to those that would be used in the Lunar Scaleable CanALSS.

3. Lunar Scaleable Canadian Advanced Life Support Systems (CanALSS)

Biological life-support systems are designed to enable sustained human planetary exploration and reduce resupply requirements from Earth. The Lunar Scaleable CanALSS would help achieve this objective by providing a portion of the crew’s air, food and water requirements.

The modular technologies developed over previous incremental steps and proposed elements would improve technology readiness and confidence for this larger-scale growth system. The CanALSS would be a significant contribution to lunar infrastructure and, in return, would provide Canada with enhanced access to further launch opportunities, lunar science returns and crew assignments for Canadian astronauts.

This element is proposed to be both modular and scaleable and will grow with incremental deployments of lunar infrastructure. This will provide continued improvements in air, food and water closure for lunar outposts or even sustained human colonies on the Moon.

The Moon will be used by the international community as a test-bed for Mars and this will apply to the development of Canadian ALS systems as well. Systems developed for the Moon would be designed with Mars foresight and be readily adaptable to the human exploration of Mars. These steps would put Canada on a path to developing biological life support systems with moderate mass closure by 2050. The goal is to obtain 50 percent food closure and considerably higher levels for air and water.

This program would permit Canada to establish an early foothold on the Moon with biological systems and provide excellent opportunities for terrestrial technology transfer, the development of highly qualified personnel and educational outreach.

Benefits to Canadians

Advancing Canadian ALS capabilities offers significant potential for terrestrial technology transfer. This aspect has been the cornerstone of current funding for research and technology development in advanced life support systems. Thus there is a direct link between space and terrestrial technology development. Several notable examples include:

- improvements in greenhouse labour and energy efficiency
- robotic horticultural management strategies
- environmental compliance management strategies in the agri-food sectors
- plant production technologies for northern and remote communities seeking more independence in food supply and distribution.
- “green” buildings and biofiltration of indoor air to mitigate sick building syndrome
- food safety and security with non-toxic residue disinfection technologies
- alternative plant pest control & water resource use efficiency
- recycling protocols for water and wastes
- ion sensor technology in nutrient management systems
- recyclable materials and recycling management strategies
- education and outreach, enhanced science and space science awareness.

Canadian ALS Roadmap

Canadian ALS efforts are focused on enabling sustainable human planetary exploration through technological advancements in food closure, air revitalization and water recycling. ALS community discussions, studies and results from the CSEW6 ALS breakout session have helped generate a roadmap for ALS research and development in Canada until 2030 (Figure 1).

It is assumed that by that time, a plant production system will be operating on the lunar surface capable of supporting a portion (e.g. 5-10%) of crew life support requirements. The progression from this operational system to a 2050 goal of a planetary plant production system capable of at least 50% food closure will be primarily achieved through operational experience obtained from this system, which will be modular in nature, allowing for expansion to accommodate an increasing contribution to life support requirements. These milestones are based on incremental advances in technology development and applications in support of space exploration initiatives.

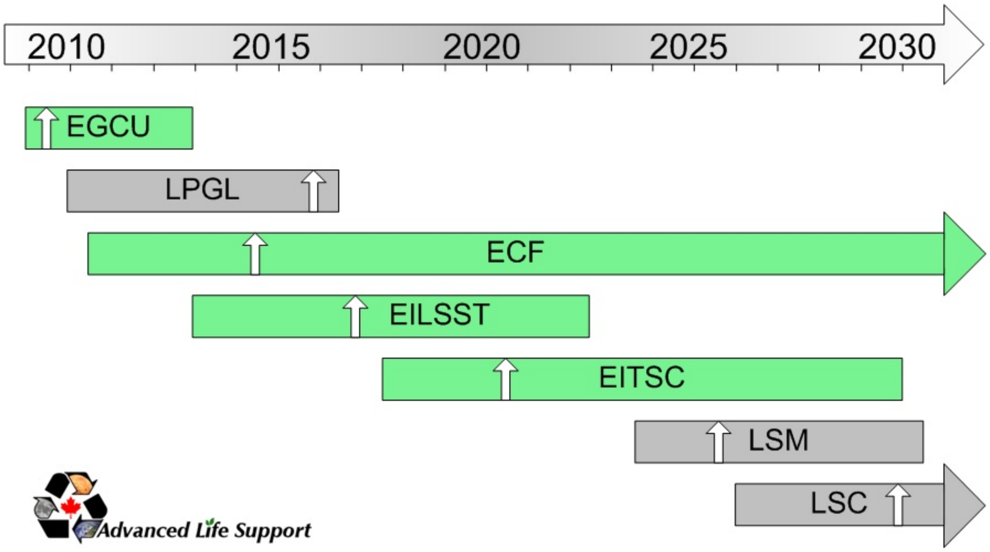

Figure 1: Canadian Biological Life Support System Roadmap (Legend: Earth Growth Chamber Utilization (EGCU), Earth Control Facilities (ECF), Earth Integrated Life Support System Test-Bed (EILSST), Earth Integrated Training and Simulation Centre (EITSC), Lunar Plant Growth Lander (LPGL), Lunar Salad Machine (LSM), Lunar Scaleable CanALSS (LSC), Vertical Arrows Represent Commencement of Full Facility Operations or Launch Dates)

7 OPERATIONAL SPACE MEDICINE

The Operational Space Medicine (OSM) Group is the Canadian Space Agency (CSA) medical body responsible for the health and safety of Canadian astronauts. The OSM group is a user of the expertise in the Canadian medical sciences community through contracts or MOU. This community's comments form the bulk of this section of the report.

The main functions of the OSM group include:

- medical operations: providing clinical and operational medical support to Canadian astronauts
- participating in projects to develop medical concepts, technologies and procedures to enhance performance and to diagnose, prevent and treat illness and injury
- developing and fostering Canadian expertise in aerospace medicine.

Because of OSM's focus on individual well-being, the approach to science in this group differs from that of other disciplines. Since Canadian astronauts are its main "clients," OSM's space exploration objectives are best thought of as medical objectives to reduce identified risks to human health during spaceflight.

The Canadian medical community has much to offer the international human space exploration program in terms of knowledge and expertise, research capacity and medical technology development. These strengths are equally applicable to space and in remote terrestrial environments.

Space medicine was identified as an important component of a balanced Canadian exploration program at a CSA-sponsored workshop entitled *"Exploration Canada 2006 :Consultations on Canada's contributions to the scientific, human, and robotic exploration of the Solar System."* At the same time, the CSA's OSM group contracted the medical community to complete its own "needs and capacity" study focused on identifying medical care solutions for long-duration human space missions. This study prioritized medical care needs and potential solutions for missions to the moon and Mars.

The Needs and Capacity Study identified the following challenges for long-duration missions:

- radiation monitoring and protection
- psychosocial and behavioural issues
- microgravity and reduced-gravity effects and related countermeasures
- crew health maintenance and medical care, including diagnostic, monitoring and treatment technologies and clinical training and maintenance of skills for crew medical providers
- telemedicine support.

The study also identified current Canadian capacity (both technological and non-technological) to meet specific needs for the space exploration program. Many of the solutions for space-related medical issues were also found to be relevant for the delivery of medical care in remote locations in Canada.

After analyzing Canadian capacity, the following three areas were deemed to be key areas for future efforts and funding:

- medical training and skills maintenance programs for remote health care providers
- telemedicine programs, including real-time and asynchronous tele-consultation capability
- developing technologies for autonomous medical care in remote environments.

Therefore, the results of previous studies and projects have reaffirmed the significance to the Canadian space medicine community of the “three Ts”: technology, telemedicine and training. Future projects that pursue interdisciplinary objectives in these and other areas would add value to these efforts.

Summary of Objectives Identified at CSEW6

- OSM-1 Clinical training and maintenance of skills for crew medical providers.
- OSM-2 Telemedicine support.
- OSM-3 Monitoring, diagnostic and treatment technologies and procedures.
- OSM-4 Human behaviour & performance.
- OSM-5 Basic physiology/human biology and countermeasures.

Objectives and Investigations

Objective OSM-1: Clinical training and maintenance of skills for crew medical providers.

What is the best way to train and maintain the medical skills of crew medical providers assigned to long-duration missions?

Crews on exploration missions beyond low-Earth orbit will require a high level of medical autonomy. This will be especially important on expeditions to Mars because of the long delay in interactive (synchronous) communications with Earth. Although some forms of consultation with experts on Earth will still be possible, it is essential to provide exploration crews with advanced medical skills and tools that will enable them to monitor, diagnose, treat and prevent illnesses and injuries, including time-critical and life-threatening emergencies, on their own.

On long-duration flights, there is likely to be at least one astronaut designated as the Crew Medical Officer (CMO), responsible for the health care of the astronauts on the mission. There is a need to develop a training program for these CMOs to ensure they have the necessary knowledge and skills. Space medicine topics could be an integrated component of a new remote-medicine training program that would also train terrestrial health care providers to function on their own in remote locations.

The first step for such a program, i.e. to develop an initial curriculum, has already been accomplished. Next steps, including implementation, will involve developing detailed learning objectives, followed by ongoing program development as well as evaluation of both participants and program effectiveness.

This work will capitalize on Canada's long-standing expertise in telemedicine, tele-mentoring, and the use of analogue environments, such as remote locations in the Arctic, that can stand in for various aspects of the space environment. Canada is already a world leader in the delivery of innovative health care education and it also has extensive experience in space robotics simulation and training.

The advancement of training in remote medicine will benefit not only astronauts but also Canadians on Earth. Canada's geography and small population dictate a need for well-trained remote health care providers. Currently, however, currently there are gaps in the provision of training for these providers. Achieving world-class excellence in this kind of training and creating highly-skilled health care providers who can function autonomously in remote environments is in keeping with the Canadian government's science and technology goals.

In addition to providing direct benefits to Canadians on Earth, this research will enable Canada to leverage the competency of remote health-care providers and Canada's expertise in simulation and robotics to strengthen Canada's international reputation and facilitate its participation in large-scale international space exploration projects.

Investigations:

1. Gather data on the incidence and prevalence of medical events in remote environments, analogue sites and the International Space Station.
2. Develop prototypes of simulated training scenarios and conduct proof of concept studies for them with medical universities and analogue sites.
3. Evaluate the effectiveness and efficiency of training on skills acquisition and retention.
4. Investigate the usability and utility of tele-health technologies, including hardware, software and infrastructure (e.g. tele-ultrasound).
5. Investigate how effectively computer-based learning systems, simulations and clinical experience enable health care providers to retain and transfer procedural skills from the training to the real-world environment.

Objective OSM-2: Telemedicine support

What are the most effective ways to use telemedical technologies to maintain astronaut health on long duration missions?

Notwithstanding the requirement to increase the medical autonomy of crews on long-duration space missions, there is also a need to enable remote crews to consult with medical experts and mentors on Earth and to receive continuing education to maintain their skills, using both real-time and asynchronous communications.

Experience at analogue sites such as Antarctic stations has shown that consulting medical support is sometimes required by even the most seasoned physician CMOs. On Mars missions, one significant challenge will be the lack of real-time communications with Earth because of the distance signals must travel between the two planets. The use of asynchronous or "store and forward" communications (during which data is saved and sent later) in this situation remains an area worthy of further evaluation. Saving data and sending it later is a technique worthy of further evaluation.

Advances in tele-consultation technologies and programs will also improve the health care available to people in remote or under-serviced areas on Earth.

Investigations:

1. Proof of concept studies at analogue sites are required to evaluate and confirm the functionality of devices used for tele-consultation. Key factors include the time it takes to transmit data, digital image quality (e.g. sonograms) and sound quality for auditory devices (e.g. stethoscopes.)
2. Proof of concept studies at analogue sites to confirm the effectiveness of medical care delivery by evaluating medical outcomes and thus the success of medical management.

Objective OSM-3: Monitoring, diagnostic and treatment technologies and procedures.

What are the best diagnostic imaging, lab diagnostic, monitoring, and surgical methods to maintain crew health and treat illness or injury on long-duration missions?

The goal is to develop, validate and test technologies that can be used for a variety of purposes and that are flexible, scalable and integrated (i.e. small and multi-use). These criteria will facilitate moving these technologies into multiple medical environments in space and on Earth and making them compatible with the delivery of telemedicine.

Some technologies (for example, diagnostic ultrasound) are known to be nearly ready for use on space missions. Others are more novel in this context and would require further investigation.

It is also important to continue to advance the ability to use minimally invasive surgical techniques (e.g. laparoscopy). Advancing our understanding of the usability of robotic applications for medical care would also be a relevant space-terrestrial overlap. This would enable the medical community to participate in discussions on important mission parameters such as mass, power and volume requirements, and to take advantage of opportunities to participate in missions that may arise once these parameters are defined.

Canada is known for developing both new medical technologies and alternative uses for existing medical technologies. It is already a leader in using tele-ultrasound, and robotic systems to remotely perform minimally-invasive surgical procedures.

The following investigations would use a variety of venues and platforms, including ground-based laboratories and analogue sites, parabolic flights on aircraft and ISS missions.

Investigations:

1. Assess and prove the feasibility of using various technologies to prevent, monitor, diagnose and treat medical conditions on space missions.
2. Evaluate equipment and procedures.

3. Evaluate operator and equipment performance.
4. Evaluate operator retention and transfer of skills between scenarios.
5. Assess and confirm adequate patient outcomes.

Objective OSM-4: Human behaviour and performance

What are the best ways to monitor, assess, maintain and enhance human performance in space?

On long-duration missions in an isolated and hazardous environment, it will be important to monitor and assess the performance, behaviour and psychological health of crew members. The goal is not only to prevent performance losses and behavioural issues, but also to find ways to enhance performance under these demanding conditions.

The international space medicine community has recognized the need to do this, but has not yet developed the tools or hardware to accomplish it. What is needed is the ability to monitor and evaluate cognitive skills using a practical, hands-on method of gathering data, such as robotic task simulations rather than paper-and-pencil tests. It is likely that international collaboration would follow if Canada took the lead.

The development of a practical assessment tool for space could be applied in other fields on Earth where the consequences of mistakes in high-stress situations are significant, such as medicine/surgery and aviation. This work will also promote partnerships based on multicultural and multinational factors.

Investigations:

1. Ground-based investigations comparing the effectiveness of hands-on to more traditional paper-and-pencil strategies for characterizing performance.
2. Evaluations of the impact of feedback on performance enhancement (i.e. does feedback lead to enhanced performance?).
3. Validation of these results at analogue sites and on the International Space Station.

Objective OSM-5: Basic physiology/human biology and countermeasures.

What is the best way to create personal countermeasure programs for space crews to counteract the effects of microgravity and the contained environment in space?

Improvements in the ability to monitor the effects of the space environment on the human body will allow us to gather more complex and individualized medical data. Such data could be used to develop a program of personalized countermeasures for each astronaut, based on their personal biology. The “one-size-fits-all” approach to countermeasures does not take into account individual variability.

It is also important to take an integrated approach to countermeasures that addresse all physiological and psychological effects of the space environment on the human body.

Canadian capacity in developing cardiac, muscle, and bone countermeasures, combined with radiation biodosimetry and gene-sequencing capabilities that developed rapidly during and after the SARS outbreak, give Canada an excellent opportunity to develop a niche in individualized/personalized countermeasures.

By building on these research strengths, Canada can further the scientific understanding of human physiology and the prevention and treatment of disease. The emphasis on developing preventative approaches and individualized care can lead to improvements in health-care delivery both in space and on Earth.

This work will also promote partnerships between the space medicine and the science communities studying life sciences, radiation and human behaviour and performance.

Investigations:

1. Ground-based laboratory investigations
2. Ground-based analogue sites
3. Parabolic flights
4. ISS missions

A Note on Investigations:

OSM has a mandate to provide for the health and safety of astronauts. This means that investigations related to space medicine objectives must be done in a staged manner, with proof of concept studies, if applicable, occurring before human testing.

The following platforms have been identified as being most relevant in the near- to mid-term to enable the types of studies needed to meet space medicine objectives. Examples of well-suited investigations associated with each type of platform are given.

- **Ground-based non-analogue** (e.g. laboratories): robotic tasks to validate human behaviour and performance
- **Analogue environments**: ground-based (e.g. Devon Island, Arctic environment): communications, simulation, training, virtual reality
- **Microgravity platforms** (e.g. parabolic flights on aircraft): procedural feasibility; technology validation; basic human biology; manifestation of disease processes in reduced gravity
- **International Space Station:** pre-, mid- and post-fight biological measurements; evaluation of skills degradation; effectiveness of tele-mentoring / coaching strategies
- **Lunar:** further testing of technologies beyond the proof-of-concept stage.

8 Space Life Science

For life sciences, the main research interest in human space exploration is focused on long-duration exposure of biological systems to the space environment. There are several significant components of this environment: reduced gravity, ranging from microgravity to one-sixth gravity on the Moon and one-third gravity on Mars; space radiation and isolated and confined living conditions that can affect human behaviour and psychological well-being. Space is the ultimate example of an ICE (isolated, confined and extreme) environment—one that can be lethal.

Life scientists are interested in using the International Space Station as a research laboratory to explore many interesting questions, such as the long term effects of reduced gravity and other aspects of the space environment on the following systems (not listed in order of priority):

1. the whole body (i.e. an integrated approach to physiological effects)
2. assessing genomic contributions to individual responses to microgravity
3. bone structure, composition and function
4. radiation biology
5. psychological health and function
6. the cardiovascular system
7. muscle structure, composition and function
8. the vestibular system and other components of the nervous system
9. developmental processes.

Because scientists have had limited access to reduced-gravity environments, there are still many unanswered fundamental questions about the response to gravity—or the lack of it—of biological systems ranging all the way from the molecular and cellular level, through tissues and organs to the whole body.

Moreover, this research has significant practical implications. All of the topics listed above can be associated with reduced task performance and health risks in astronauts. For example, changes in bone mass can be linked to an increased risk of fractures, while reduced muscle strength or loss of physical fitness can impair the ability to perform required work tasks and emergency activities.

A better understanding of the biological and physiological changes that occur in reduced gravity environment is key to reducing the health and safety risks faced by crews on long-duration missions. For instance, insight into the nature of cellular and other changes that occur within bone in reduced gravity will lead to new approaches in treating and preventing bone loss both in space and on Earth.

It is important to note that the objectives of space life sciences overlap those of operational space medicine (OSM), which is tasked with monitoring, treating and preventing illness and injury among space crews.

Similarly, studying the effects of space radiation can further the objectives of both space life sciences and operational space medicine. It is known that crews on exploration missions will face increased radiation risks, especially when they venture beyond low-Earth orbit where they receive some protection from the Earth's magnetic field. However, relatively little is known about the nature of the radiation environment in space and exactly what kind of biological damage this radiation can cause. These details will be important in developing radiation protection and countermeasures to protect crews.

Scientists also need to gain a better understanding of the consequences of altered levels of physical activity on musculoskeletal and cardiovascular fitness for performing daily life and work tasks and for astronaut health.

Finally, it is important to understand the psychological effects of living in isolated, confined and hazardous environments (spacecraft or planetary colonies) for long periods of time, especially when crews are comprised of a mixture of genders, nationalities, cultures and races. It is important for both science and safety to understand the effects of these extreme environments on human behaviour and performance and the potential operational risks they can create.

Developing countermeasures (such as medications, new technologies and nutrition and exercise programs) to reduce or prevent the adverse effects of exposure to the space environment is a central goal of both space life sciences and operational space medicine. The Canadian life science community can make a significant contribution in this area by working to develop countermeasures based on individual responses rather than "one-size-fits-all."

Genetic variations among humans means that different people respond differently to pharmaceuticals and other interventions; gaining a better understanding of these differences will enable scientists to develop more effective and targeted countermeasures. Identifying individuals with specific genetic risk for microgravity-associated impact will be critical to developing effective countermeasures.

It is also important to develop integrated countermeasures that take into account all the physiological systems that may be affected, rather than concentrating on each one separately. Experience has shown that interventions may sometimes have unpredicted negative effects on non-targeted systems. This is another area in which Canadian life science researchers can make an important contribution.

Finally, studying the physiological effects of reduced gravity may have another valuable spin-off effect. There are parallels between the human body's response to microgravity and the aging process, so this research may help scientists improve health care for the elderly on Earth.

Summary of Objectives

- SLS-1 To better understand the risks to living organisms of radiation exposure beyond low-Earth orbit and develop countermeasures.
- SLS-2 To better understand biological and physiological changes that occur in reduced gravity environments and develop countermeasures.
- SLS-3 To develop a more integrated understanding of the biological and physiological effects of the space environment and develop integrated countermeasures.

- SLS-4 To better understand the psychological effects of spaceflight and develop countermeasures.
- SLS-5 To develop equipment to collect radiation, biological and physiological data during spaceflight.
- SLS-6 To encourage the clinical and research communities to work together.

Objectives and Investigations

Objective SLS-1: To better understand the risks to living organisms of radiation exposure beyond low-Earth orbit and develop countermeasures.

Currently, scientists have an incomplete understanding of the nature of the radiation environment beyond low-Earth orbit and little understanding its short and long-term effects on biological systems. There is a need for more detailed knowledge of the damaging effects of space radiation all the way from DNA to whole organisms. And it is not just the effects on humans that are of concern: plants and animals will also play a significant role in space exploration. Plants, for example, will be an integral part of the life-support systems of spacecraft and planetary colonies by providing both food and oxygen.

Investigations:

1. Investigate the effects of radiation on whole organisms (e.g. fruit flies or nematodes) over multiple generations. This would shed light on the types of mutations that are likely to accumulate over time and provide insight into the long-term risks of radiation exposure beyond low-Earth orbit.
2. Investigate the immediate and long-term effects of radiation at the cellular level and identify exactly how radiation damages cells and DNA.
3. Develop targeted countermeasures to reduce the risk of radiation exposure beyond low-Earth orbit, including drugs, dietary interventions and exercise.

Objective SLS-2: To better understand the biological and physiological changes that occur in reduced gravity environments and develop countermeasures.

It is known that all major systems in the body are affected by reduced gravity. Among the most significant are the bones, the muscles, the heart, the neurological system and the vestibular (balancing) system. These effects have implications for both the operational efficiency and safety of space exploration missions and for the immediate and long-term health of the crews.

It is important to understand the changes that occur in space at all scales from the smallest (molecular, cellular) to the largest (tissues, organs, whole body) in order to develop more effective countermeasures. For example, understanding how the reduction of heart and skeletal muscle mass might impair the ability of astronauts to complete required work tasks or perform emergency operations can influence the nature of prescribed physical activity programs to improve crew health and safety.

It is also important to understand biological and physiological effects in non-human organisms, such as plants, that are a significant component of the life support system.

Investigations

1. Investigate the molecular and cellular basis for biological and developmental changes in living organisms as a response to reduced gravity.
2. Investigate physiological changes that occur in organisms living in reduced gravity, from the cellular to whole-body level.
3. Develop countermeasures to reduce negative biological and physiological effects from living in reduced gravity, including: medications; exercise; dietary and nutritional interventions and technologies, such as lower body negative pressure, artificial gravity, computer systems and procedures.

Objective SLS-3: To develop a more integrated understanding of the biological and physiological effects of the space environment and develop integrated countermeasures.

To date, much of the scientific investigation into the biological and physiological effects of the space environment has focused on individual systems such as the bones, the heart or the vestibular system. It is important to develop interdisciplinary studies that target not just parts of the body but the whole body as an integrated system.

This is particularly important when developing countermeasures to ensure that interventions aimed at one system do not cause harm in other systems. It would also be useful to develop countermeasures that are effective in several systems at once, thereby reducing the number of countermeasures that must be applied and the risk of negative interactions between them.

Investigations:

1. Develop a database of genomic predictors of responses to microgravity based on Earth-based pre-clinical and analogue studies that can then be validated on ISS in both retrospective and prospective studies.
2. Assemble interdisciplinary research groups to conduct ground-based studies on a variety of physiological systems, using the same patients and sharing data. One example would be to use bed-rest studies that simulate reduced gravity environments to study the effects on bones, muscles and the cardiovascular, neurological and vestibular systems.
3. Use an integrated approach to collecting and interpreting data during space missions.
4. Use data from integrated research studies to develop countermeasures that effectively target multiple systems and/or do not cause unexpected adverse effects in non-target systems.

Objective SLS-4: To better understand the psychological effects of spaceflight and develop countermeasures.

Astronauts typically work in confined, isolated and hazardous environments. This can have a psychological impact and affect their behaviour and performance even during relatively short missions in low-Earth orbit. When they venture farther afield to the Moon and Mars, these factors will only be compounded by the longer duration of the missions, the increasing distance from Earth and the lack of real-time communication that will accompany it.

Experience with crews working in similar environments on Earth (e.g. Antarctic research stations and isolation chambers) has shown that crews can experience a range of emotions and conditions (depression, fear, pain, anger, fatigue, withdrawal), leading to interpersonal conflicts and a loss of performance that could be serious enough to threaten the mission. Additional stresses can be introduced when crews include mixed genders, nationalities, cultures and races.

On long missions beyond low-Earth orbit, such as a trip to Mars, the early return of some or all crew members to Earth will not be an option. Therefore, it is important to develop enhanced techniques for selecting compatible crews and to identify the potential for psychological stress that may affect behaviour and performance and disrupt long-duration missions. Furthermore, the identification of appropriate and validated biomarkers and psychological assessment tools to define increases in risk during missions is needed so effective interventions can be initiated before they develop into serious problems or complications.

Investigations:

1. Improve understanding of the biological, psychological and social effects of stress in an ICE environment and develop new approaches to treat and prevent them (e.g. exercise, nutrition, medication, counseling, etc.).
2. Model the human decision-making process and personal and social information processing. Why do people do the things they do?
3. Investigate the emotional needs of crews (e.g. food and eating rituals, companionship, community-building, comfortable living conditions).
4. Develop methods to measure and evaluate human performance and behaviour on long-duration missions.
5. Investigate the potential of biofeedback as a tool to help people perform and function better in the space environment.
6. Develop new technologies with improved machine-human interfaces to reduce the work burden on crews (e.g. natural language input, intelligent data management).
7. Develop astronaut selection criteria designed to find crew members who are psychologically suited to working with a team on long-duration missions.
8. Develop and validate biomarkers and assessment tools as indicators of enhanced psychological risk to enable development of effective interventions.

Objective SLS-5: To develop equipment to collect biological, physiological and radiation data during spaceflight.

There is a need to increase and improve the array of equipment and instruments available to collect biological and physiological data in-flight and transmit it to Earth. An increase in the amount and type of data collected is necessary to develop more effective and targeted countermeasures.

Investigations:

1. Develop equipment that can analyze blood and urine biological samples in flight rather than sending them back to Earth for analysis. This would enable the measurement of metabolites that are medically and physiological important (e.g. proteins that can indicate increased risk for cardiovascular disease) and a more rapid therapeutic response.
2. Investigate the introduction of medical technologies not previously used in space to improve the ability to detect and treat illness and injury during missions. For example, one potentially useful technique is flow cytometry, which measures microscopic particles flowing in a fluid stream through a laser beam.
3. Develop detection systems that can monitor for the presence of microbial pathogens (e.g E. coli) in real time. This is a field in which Canadians have expertise.

Objective SLS-6: To encourage the clinical and life science research communities to work together.

The space life science and OSM communities share many similar goals related to improving understanding of the effects of the space environment on living organisms. OSM's mandate is to monitor, diagnose and treat astronauts for illness and injury before, during and after space missions; to maintain their health and safety and to develop countermeasures to prevent the adverse effects of exposure to the space environment, including reduced gravity, increased radiation and isolation and confinement.

Accomplishing these tasks requires a solid base of scientific data provided by the space life science community. Closer co-operation between the two groups will ensure that scientific investigations will target areas of greatest need and that the results will ultimately be translated into effective treatments and countermeasures that will save lives. This type of co-operation will also improve the delivery of health care on Earth.

9 Space Radiation

One of the most serious risks faced by humans on exploration missions beyond low-Earth orbit is exposure to space radiation. Once past the protection of the Earth’s magnetic field and atmosphere, astronauts will be exposed to a variety of energetic particles, including neutrons and electrically-charged high-energy protons and heavy ions. All are capable of damaging human genes and causing cancer. In addition, there is an emerging association between radiation exposure and non-malignant disease, principally cardiovascular disease.

Space is awash in cosmic radiation streaming in from outside the solar system. Space crews can also be exposed to damaging and potentially lethal doses of radiation from solar flares. Flares are especially dangerous to astronauts working outside their spacecraft.

In addition, high-energy particles can interact with materials in the spacecraft, and even with the tissues of the human body, to create secondary radiation in the form of neutrons. At times, this can result in higher radiation levels inside a spacecraft than outside. Canadian research indicates that neutrons could account for about half of the radiation astronauts are exposed to. Scientists around the world are currently working to gain a better understanding of the space radiation environment to properly assess the danger to exploration crews. They are also developing real-time radiation monitors and spectrometers, as well as working on protective countermeasures, such as shielding and drugs that protect against some kinds of radiation damage.

Summary of Radiation Objectives

- RAD-1 Quantitative radiation measurements (metrology):
    a. Develop real-time personal radiation monitors for space crews
    b. Develop real-time detectors that can discriminate between neutrons and primary protons
    c. Develop methods of measuring radiation based on the number of particles interacting with matter rather than how much energy is deposited, which may be more relevant to the radiation environment in space.

- RAD- 2 Radiation Modeling:
    a. Develop computer codes that can simulate the interaction of radiation with detectors and instruments to better understand instrument behaviour and response
    b. Improve the ability to shield crews from space radiation
    c. Develop methods for modeling DNA damage caused by space radiation.

- RAD-3 Radiobiology:
    a. Improve understanding of the long-term risks of radiation exposure in space, including non-cancer risk
    b. Identify biomarkers (e.g. activated genes or elevated levels of specific proteins resulting from gene activity) that can be used to measure the biological risk of radiation exposure in space.
    c. Develop drugs that can protect against moderate to high doses of space radiation.

Objectives and Investigations

Objective RAD-1a: Metrology: Develop real-time personal radiation monitors for space crews.

The radiation environment in space is complex; it involves a mixture of different particle types with different linear energy transfer (LET), and it varies over time.

LET describes how much energy is deposited by a charged particle over a very small part of its path. Knowing this will help determine the amount of energy available to damage very small targets, like the DNA in the nuclei of cells.

It is important to have real-time monitoring of what is going on in this environment to protect crew members. Canada has a long history of research on radiation related to its defense and nuclear power activities and therefore has considerable expertise in developing radiation detectors or dosimeters.

Investigations:

1. Ground-based facilities for testing and calibrating radiation monitoring instruments. It is essential to have ground-based laboratories using beams of heavy ions that simulate cosmic rays, energetic particles that stream in from beyond the solar system. It is difficult to test these instruments in space because of limited access to space flights, so ground-based testing is critical to developing better instruments in a timely manner. NASA’s Space Radiation Laboratory at the Brookhaven National laboratory is a good example of such a facility. There are other laboratories in Japan and Germany. Negotiated access to these facilities for CSA work and/or the development of beam-lines dedicated to space radiation work at the TRIUMF facility in BC would provide researchers with the tools they need to develop new instruments.

Objective RAD-1b: Metrology: Develop real-time detectors that can discriminate between neutrons and primary protons.

Many existing neutron dosimeters and spectrometers cannot discriminate between neutrons and primary protons, or their response to high-energy protons is not known. It is important to know the dose distribution among different radiation types because each has its own characteristic effectiveness in creating biological damage. This makes it important to know the exact composition of the radiation fields in space.

Investigations:

1. Ground-based facilities for testing and calibrating real-time radiation detectors.

Objective RAD-1c: Metrology: Develop methods of measuring radiation based on the number of particles interacting with matter rather than how much energy is deposited, which may be more relevant to the radiation environment in space.

The radiation environment in space is very different from that experienced on Earth in terms of the energy and linear energy transfer (LET) of particles, as well as the structure of the particle track (the energy deposited around the particle's path as it travels through biological matter.) Quantities, such as absorbed dose (the total amount of energy deposited), may not be sufficient to express the actual risk, which may depend on the exact nature of the energy deposited by the radiation at the cellular or sub-cellular level. This, in turn, will depend on the characteristic pattern of energy deposited around the path of the charged particle.

Improvements in determining risk may be possible using measures of particle track-structure and the number of particles that interact with cells over time, known as the fluence.

Investigations:

1. Generating ground-based data on charged particle interactions.
2. Computer simulations of particle tracks.

Objective RAD-2a: Modelling: Develop simulation codes for instrument response modeling.

Developing instruments for measuring radiation in real-time based on active devices (e.g. proportional counters and scintillation counters) depends critically on being able to develop models to predict and understand their responses to different energies of radiation. There are existing computer codes to help with this task, but custom codes are needed to complete the detailed modeling of charged particle interaction with the instruments. This research will be valuable to the wider radiation science community in Canada.

Investigations:

1. Coordination between different groups with experience in using existing and custom codes for simulating detector responses to different radiation fields.

Objective RAD-2b: Modeling: Improve the ability to shield crews from space radiation.

A significant portion of crew exposure comes from secondary radiation created when high-energy particles hit materials used in spacecraft, including materials used for radiation shielding. It is necessary to gain a better understanding of how radiation is transported through these materials in order to create more effective shielding.

Investigations:

1. Computer simulations of radiation interactions with matter to evaluate different materials for shielding flight crews from cosmic rays.
2. Based on these findings, optimize shielding thickness, material and location on mission vehicles or permanent settlement habitats.

Objective RAD-2.3: Modeling: Develop methods for modeling DNA damage caused by space radiation.

DNA is damaged by a complex interplay between charged particles and the structure and environment of the DNA itself. This damage is the precursor of most of the biological effects of radiation and understanding it is critical to determining how effective one type of radiation is compared with another in creating equal biological damage.

This research will be useful not only in space medicine, but will also be useful in radiation protection and radiation applications in general medicine.

Investigations:

1. Consolidate Canadian expertise in DNA damage modeling research. Canadian researchers who can do work on modeling DNA damage by radiation are dispersed across the disciplines of medical physics and health physics. Support is needed to enable these scientists to work together to establish DNA-damage modeling codes applicable to space radiation.
2. Develop damage-modeling codes that can deal with the physics and track structure of heavy charged particles present in space radiation fields.

Objective RAD-3a: Radiobiology: Improve understanding of the long-term risks of radiation exposure in space, including non-cancer risks.

It has been known for a long time that radiation exposure increases the risk of cancer but there is emerging evidence that such exposure can also cause non-cancer effects like cardiovascular disease. Learning more about these effects will benefit the development of radiation protection on Earth as well as in space. Canada has developed techniques and protocols for animal studies in this field.

Investigations:

1. Lifetime animal studies. To make progress in understanding long-term risks of radiation exposure to participants in space exploration missions, it is essential to conduct studies of the effects of chronic radiation exposure over the entire life of an animal for all disease types and eventual causes of death. Experimental animals would be irradiated using different radiation protocols and then followed for the remainder of their life. The causes of death and the state of different tissues and organs at the time of death would be recorded to identify associations between exposure level and the type and the appearance of disease and organ failure. In order to conduct these studies, it is necessary to have access to ground-based radiation facilities for neutrons, energetic protons and heavy ions that can simulate the radiation fields that exist in space, as well as facilities for the life-time care and study of the experimental animals.

Objective RAD-3b: Radiobiology: Identify biomarkers (e.g. activated genes or elevated levels of specific proteins resulting from gene activity) that can be used to measure the biological risk of radiation exposure in space.

Changes in chromosomes that contain our genes are known biomarkers of radiation damage. Counting the number of aberrations in chromosome structure following a radiation exposure can provide a measure of biological damage and risk from radiation exposure. Other biomarkers may also be useful indicators of radiation exposure and will be easier to measure in exposed crew members. One example is measuring changes in gene regulation—specific genes being switched on and off—and resulting changes in protein levels. Identifying these additional biomarkers would also be extremely useful in managing radiation events in populations on Earth. Canada has been active in this field through its support for research and development for counter-terrorism activities.

Investigations:

1. Identify possible markers and develop radiation-exposure and assay protocols to prepare dose-effect curves that will allow the exposure of individuals to be assessed. By measuring biomarkers in blood samples, scientists should be able to determine how much radiation individuals actually received and their risk of biological damage.

Objective RAD-3c: Radiobiology: Develop drugs that can protect against moderate to high doses of space radiation.

Developing radio-protective drugs would have great significance not only in the space program but also in civil and military applications on Earth. Canada cannot develop these drugs from scratch, but it could play a significant role in screening natural substances that may have radio-protective effects.

Investigations:

1. Develop facilities for animal studies to develop drugs for radiation protection. Scientists working to identify possible radio-protective drugs and substances usually work with cell cultures. However, potential radio-protectors ultimately have to be tested on animals to evaluate their effect on the whole organism. There are few suitable animal facilities and they are used for different purposes, so it is important for research groups to coordinate in-vitro assessments and eventual animal testing of promising radio-protector candidates.

10 Space Physical Sciences

Space physical sciences focus on understanding the role of gravity, radiation and other aspects of the space environment on physical and chemical systems, and on using the low-gravity space environment to study physical phenomena not experimentally accessible on Earth. This research not only enables the exploration of space, but, equally important, it allows scientists to use unique features of the space environment to answer questions about important physical and chemical processes on Earth.

Research in the physical sciences is essential to the success of future human and robotic space exploration in and beyond low-Earth orbit. Canadian space physical science encompasses investigations in materials science, fluid physics, combustion, biotechnology and nanoscience. It addresses key issues that will enable future human exploration of space and planetary surfaces, including:

- the development and risk mitigation of spacecraft sub-systems, sustainable planetary habitats and sub-systems, life support systems, tools, vehicles and materials
- the maintenance and monitoring of health, safety and productivity of human crews
- the ability to reliably and efficiently extract and use resources (energy, oxygen and materials) from the space environment and from other planets
- the ability to conduct scientific studies to answer questions about the nature, history and evolution of the solar system and the universe.

Canada's scientific community already has a great deal of expertise in space physical sciences, having participated in missions stretching from the early days of human long-duration fights in the 1970s to current and scheduled experiments on the International Space Station. This work has fostered partnerships among universities, government and industry in Canada, as well as co-operation among governments and with the international scientific community.

Further research in this area is consistent with the Government of Canada's Science and Technology Strategy; it helps to maintain Canada's excellence in science and addresses its key priorities like: energy, environment, health, biotechnology, communications technologies and materials science.

Summary of Physical Science Objectives

The following broad scientific objectives have been identified as being fundamental, practical, and of strategic importance to Canada's role in space exploration:

- SPS-1 The effect of gravity on fluids and the behaviour of fluids and fluid interfaces in different gravitational environments.
- SPS-2 The effect of the space environment on materials and material processes.
- SPS-3 The effect of the space environment on combustion.
- SPS-4 The effect of the space environment on biotechnology.
- SPS-5 Nanotechnology developed on Earth that could be needed for space exploration.
- SPS-6 The effect of the space environment on heat and mass transfer.

- SPS-7 The physical science required to enable *in situ* resource utilization (ISRU)
- SPS-8 The effect of dust on space systems
- SPS-9 Physical science required to improve the efficiency of energy conversion
- SPS-10 The interactions of radiation with matter/materials

Objectives and Investigations

Objective SPS-1: The effect of gravity on fluids and the behaviour of fluids and fluid interfaces in different gravitational environments.

Many aspects of space exploration involve fluids. Fluids play a critical role in the operation of both human and non-human-rated spacecraft systems, such as liquid propellant management; fuel cell function; heating and cooling; waste-water management and oxygen generation systems. Successful space exploration missions require a good physical understanding of how these systems work in the space environment. Spacecraft life support and health care systems also require handling fluids from drinking water to blood samples. Finally, scientific investigations and experiments, including studies of the space environment itself and planetary surfaces, will require a detailed understanding of fluids, from pumping liquids to energy production to heat transfer.

Fluid handling, sampling and storage will be important in all of these activities. Canada's heritage in this field is important for efficient development of the knowledge needed for space exploration. Gravity affects the properties and behaviour of fluids so it is essential to understand the influence of different gravitational intensities—not only microgravity in space, but also one-sixth gravity on the Moon and one-third gravity on Mars. Combining the research done in these different environments by Canadian scientists and industry has a high probability of optimizing Earth-based processes involving fluids.

Investigations:

1. **Measuring and predicting the geometry of fluid in tanks.** On Earth, the placement of fluids is dominated by gravity and they remain at the bottom of a tank. In space applications, the low level of gravity means that the placement of fluid in a tank is dominated by surface phenomena (e.g. surface tension, wetting etc.) In addition, every motion of the spacecraft and the activities within it contribute to accelerations experienced by fluids in a tank, which vary in magnitude and direction and can even be rotational. Understanding the complex behaviour of fluids in tanks is essential for designing pumps, gauges and other fluid-handling devices for spacecraft. New spacecraft designs are now implemented using knowledge from fluid geometry data.

2. **Understanding and predicting the effect of gravity on contact angle and wetting.** The contact angle that a fluid interface makes with a solid and wetting determine fluid behaviour in multi-phase low-gravity systems, such as the fluid position in tanks discussed above. Before Canadian research into the interaction of gravity and contact angle, it was thought that contact angle was fixed only by the nature of the materials in contact. However, low-g and variable-g experiments and

concomitant CSA-supported surface thermodynamic theory have demonstrated that gravity profoundly influences contact angle. Understanding the interaction of fields and contact angle will change the way we model many fundamental processes on Earth. Multi-phase fluid systems appear in almost every aspect of Canada's resource-based industry and fluid interfaces interacting with solid surfaces are important in several future microfluidic and nano-technologies.

3. **Understanding and predicting the behaviour of free surfaces in space, including surface tension-driven convection (Marangoni) effects.** Free surfaces occur in many Earth-based processes such as float zone refinement of crystals. The behaviour of free surfaces in low-gravity environments is extremely complex as inertial and surface forces are often comparable. If the gravity is low enough, complicated surface phenomena that are overwhelmed by gravity effects on Earth can be studied alone. One interest is Marangoni phenomena, which occur because temperature gradients lead to surface tension gradients that set up complicated surface flows, affecting heat and mass transfer from surfaces. Marangoni phenomena are present anywhere there is a free-fluid surface and a temperature gradient, something one expects to encounter in the low-gravity, variable thermal environment of space platforms.

4. **Quantifying the effect of external vibrations on fluid behaviour and how this will affect scientific experiments.** Canada seeks to be a world leader in investigating the impact of vibration in space environments on fluid behaviour and designing equipment to isolate fluid experiments from vibrations. It is important to characterize the vibrations present in each new space platform, both in acceleration level and frequency and in six degrees of freedom—three linear and three rotational. Vibrations vary with spacecraft movement and activities on the space platform and it is important to understand how they affect fluid systems and fluid experimental results.

5. **Measuring diffusion in multi-component fluids.** Diffusion is central to most processes involving transport of molecules, including biological systems, the industrial production and processing of materials from metals to polymers, and the extraction of oil from the Earth. Yet diffusion coefficients required for computer modeling are extremely difficult (and sometimes impossible) to measure on Earth because of the presence of buoyancy-induced convection which dominates transport in Earth's gravity.

6. **Measuring the effects of gravity on multi-phase flow (gas-liquid, liquid-liquid, gas-solid, liquid-solid).** These flows are significantly changed by gravity. Phase-change processes are important in key technologies that involve energy-producing cycles and heat transfer. Multiphase flows also include gas-solid flows, such as dust movement and control, or studying the combustion of suspended dusts.

Objective SPS-2: The effect of the space environment on materials and material processes.

Every material used in space exploration (metals, plastics, ceramics, semiconductors, fabrics) can be affected by the environment in space and on planetary surfaces, which feature variable gravity levels; temperatures; pressures; different chemical and atmospheric environments; dust and debris; vibrations and radiation.

Understanding these effects and using this knowledge to develop new or enhanced materials optimized for use in the space environment is a key goal of space physical sciences in support of space exploration. This research will not only improve materials used in the space program, but will also generate the fundamental understanding needed to create better materials on Earth.

Materials experiments in space involve processes such as solidification, deposition, precipitation, purification and dissolution of materials. New techniques for procuring and handling samples are also required.

Investigations:

1. Quantify the effects of varying gravity, temperatures and pressures on materials, including alloys, ceramics, biomaterials and material coatings. Current and planned space material experiments on ISS-exposed research facilities are targeted.
2. Understand the influence of varying chemical and atmospheric conditions; radiation levels; space debris and vibrations on materials, including alloys, ceramics, biomaterials and material coatings.
3. Clarify the effects of temperature cycling on new metal alloys and nanomaterials. Spacecraft surfaces and systems can be subjected to extreme temperature cycling of hundreds of degrees over short periods of time.
4. Understand the effects of low pressure and temperature cycling on high-dexterity cloth fabrics, nanofabrics and synthesized materials and fabrics (e.g. spacesuits and their components).
5. Develop, evaluate and validate closed life-support (human) habitat materials (e.g. metals, alloys, ceramics, biomaterials, nanomaterials) and materials required for *in situ* resource utilization.

Objective SPS-3: The effect of the space environment on combustion.

Fire is one of the most serious hazards that space exploration crews may face. Many features of the space environment, such as low pressure, cyclical environmental temperatures and reduced gravity, have been shown to affect combustion in space. It is important to increase our understanding of these effects on combustion processes in order to build more secure spacecraft, habitats and space suits.

This knowledge also improves our understanding of combustion processes on Earth and Earth-based energy production. Combustion experiments in the space environment enable scientists to isolate radiative heat transfer, which clarifies the relative magnitudes of radiative and convective heat transfer in Earth-based combustion processes.

Investigations:

1. Quantify the role of the space environment on fire suppression and prevention systems.

2. Understand the underpinnings of flame attachment and stability that control the flame spread.
3. Develop fire-detection systems suitable for spacecraft.
4. Understand the role of the space environment on flame propagation and soot formation.
5. Quantify the heat transfer from flames and flame propagation as a function of the varying space environment.
6. Understand the role of the space environment on flame spread rates over materials ranging from fabrics to spacecraft structures.
7. Develop, evaluate and validate the tools for conducting hazard analyses, including skin-burn times and toxicity levels in enclosed life-support systems.
8. Characterize the role of gravity on the flammability of fabrics, textiles and coatings.
9. Understand the role of gravity on fire dynamics (e.g. flash-over times, characterizing fire growth curves).
10. Develop, evaluate and validate new fire-retardant sprays, materials and technologies.

Objective SPS-4: The effect of the space environment on biotechnology.

Long-duration space exploration will require the use of biotechnologies for environmental control and plant growth in space habitats. In addition, there will be a need to collect, prepare, store and preserve biological samples for medical and research activities.

Cryopreservation is currently the only method for the long-term preservation of biological cells and tissues, and Canada supports world-leading research in cryobiology.

Investigations:

1. Understand the role of diffusion, boundary layers, crystal growth, convection and radiation in the storage and aging of biological samples.
2. Characterize the effect of the space environment on bioreactors used to grow cell cultures.
3. Develop, evaluate, and validate replacement cell and tissue (cell and tissue therapy) technologies for use during long-duration human space travel.
4. Develop, evaluate and validate blood transfusion requirements (e.g. freeze-drying blood). There is an urgent need to take blood on long-duration missions and to take blood samples back to Earth.
5. Develop efficient technologies to collect, prepare and store biological samples in reduced-gravity conditions.
6. Maintain Canada’s scientific leadership in thermodynamic modeling of cryobiology processes.
7. Develop, evaluate and validate energy and volume-efficient cryopreservation technologies.
8. Resolve scientific issues related to the effects of reduced-gravity conditions on environmental control and plant growth systems to deliver water and nutrients and regulate temperature, climate and light exposure.

Objective SPS-5: Nanotechnology developed on Earth that could be needed for space exploration.

Nanomaterials and nanofabrication processes currently use different mechanical, optical and/or electrical behavior at the nanoscale to build coatings or bulk nanostructured materials with enhanced mechanical properties and/or wear resistance. This has great potential for application to space exploration. New materials required to sustain extreme temperatures, mechanical stresses and long-duty cycles will be of paramount importance for long-term space exploration and would have many terrestrial applications. A new generation of smart and multifunctional materials are required.

Furthermore, nanomaterials (like nanofibers or nanoparticles, as well as nanofabrication processes, such as nanolithography) allow the fabrication of low-weight, highly sensitive nano-senosr systems able to detect single molecular interaction. When integrated with lab-on-a-chip technologies, these nanosensors can be used to develop miniaturized analytical tools for on-site sample preparation to detect and quantify chemical or biochemical species.

Canada is a leader in nanomaterials research and system integration and in creating analytical tools for medical diagnostic, environmental monitoring, or monitoring biological processes related to aging, regeneration of tissues or neuroscience.

Investigations:

1. Develop, test and validate new nanostructured multifunctional fabrics using nanofibers with enhanced mechanical, electromagnetic and biochemical protection.
2. Develop material compositions and fabrication processes able to produce multifunctional coatings with energy harvesting and enhanced mechanical and wear resistance.
3. Develop methods and lab-on-a-chip systems for rapid diagnostics of infectious diseases or food and water-quality monitoring.
4. Identify methods for rapid molecular separation using nanofluidics-based total analysis systems and magnetic or electrically-active nanomaterials, to be used for on-site identification of polar and non-polar molecules in soil, ice or water samples.
5. Develop, evaluate and validate methods and systems able to characterize the effects of gravity on neurotransmitters using in-vitro models combining integrated lab-on-a-chip systems and cell/tissue culture models.
6. Develop, test and validate nanofabrication technologies able to produce single-molecule detection systems based on spectroscopic methods.
7. Develop methods and systems able to detect and quantify the effects of long-term exposure to space radiation using biologically-based approaches.

Objective SPS-6: The effect of the space environment on heat and mass transfer.

Gravity, temperature, pressure and other aspects of the environment in space and on planetary surfaces will have a significant effect on the transfer of heat and mass in many critical space systems, including those needed for life support, sustainable habitats, energy production and temperature regulation. This area of research will also improve fundamental knowledge of planetary environments.

Investigations:

1. Understand the role of gravity on evaporation and condensation. This is required for efficient energy production and regulation in space.
2. Characterize the role of heat transfer resulting from pressure differences and thermal cycling (temperature swings) on space systems.
3. Evaluate and validate heat-transfer coefficients for devices that will be used in space and on the Moon and Mars. This knowledge will be used to develop heating, cooling and thermal regulation systems.
4. Understand phase-change heat transfer in porous media such as heat pipes, capillary-pumped loops and loop-heat-pipes for transporting liquids. This is important for efficient heating and cooling of scientific equipment and human-rated spacecraft and habitats.
5. Investigate and optimize systems that control the storage, regulation and flow of gasses for closed life-support systems used in habitats and during extravehicular activity.
6. Understand the effect of gravity on the rate of sublimation (transformation of a solid to a gas without going through a liquid phase) on planetary bodies. This information would, for example, be useful in predicting the water cycle on Mars.

Objective SPS-7: Physical science required to enable *in situ* resource utilization (ISRU).

Canada is a recognized leader in developing technologies to utilize resources, particularly mining and extractive technologies. It has the technology to separate ores from rocks and scientific leadership and expertise in colloidal science and interfacial phenomena (liquid-liquid and liquid-solid mixtures) because of work related to the Alberta oil sands and the Hibernia offshore oil fields. As a result, Canada is well positioned with world-class expertise to contribute to the development of ISRU science and technology for space exploration.

Investigations:

1. Develop, test and validate sub- and integrated systems to extract water and/or oxygen from lunar and Martian soil compositions. This includes microwave extraction and water electrolysis, liquid dissolution and electrolysis and magma electrolysis among other techniques.
2. Regeneration and storage of life-support and fuel-cell power consumables.
3. Develop, test and validate sub- and integrated systems to extract liquid propellants from lunar soil compositions (e.g. oxygen and methane for robotic and human vehicles, gases for science and cleaning.)
4. Investigate and test efficient energy extraction from planetary environments. This includes developing highly efficient solar cell technologies, as well as systems to naturally harvest heat and cooling from planets (e.g. solar arrays, concentrators, rectenna, thermal wadis).

Objective SPS-8: The effect of dust on space systems.

Dust, which is a major risk to operations on planetary surfaces, is known to be prevalent on the two planetary bodies that are the primary targets of robotic and human exploration: the Moon and Mars. It can interfere with the performance of a wide range of critical equipment, including rovers, life support systems, extravehicular activity (EVA) suits and scientific instruments. Developing systems to mitigate the effects of dust will be essential in reducing the chances of mission failure.

New dust handling technologies will be transferable to Earth-based operations like mining, medical environments and materials production industries. Enhanced knowledge about dust interactions will also have Earth-based applications (e.g. wear on materials).

Investigations:

1. Characterize the electrical, physical and chemical properties of dust on the Moon and Mars.
2. Understand the physical processes involving dust, including settling, aggregation and sticking. Controlling dust concentrations on and removing dust from spacesuits and inside spacecraft and habitat modules has been identified as critical to sustained human presence in space.
3. Measure and predict the interaction of dust with space systems such as space suits, electrical and mechanical systems, airlock seals and closed life support systems
4. Quantitatively investigate dust handling and filtering in support of the objectives previously identified

Objective SPS-9: Physical science is required to improve the efficiency of energy conversion.

Energy systems are critical components of all space exploration activities. New efficient energy technologies will be required to power spacecraft beyond low-Earth orbit, create sustainable habitats on planetary surfaces, for life support, surface transportation and scientific experiments and expeditions.

Canada is a world leader in developing many of these energy-storage technologies; expertise must be applied to the benefit of Canadian space exploration.

Investigations:

1. Semiconductors for solar to electrical conversion and certification for spaceflight.
2. Fuel-cell technology and certification for spaceflight.
3. Electrical energy storage and certification for spaceflight.
4. Nuclear power requirements for human long-duration planetary exploration missions.
5. Materials and systems for more efficient thermo-electric energy conversion for space applications.

Objective SPS-10: The interactions of radiation with matter/materials.

Understanding and characterizing radiation sources from the space environment is of paramount importance for sustained human presence in space. Working in collaboration with monitoring space radiation, this objective targets the development of new materials to protect spacecraft by shielding the systems and life within to reduce risk and increase the safety of space exploration.

Investigations:

1. Define the space radiation environment as it relates to humans.
2. Develop, evaluate, validate and implement materials and nanocoatings to improve radiation shielding and protect spaceflight operations.
3. Develop, evaluate and validate materials and coatings to protect humans from space radiation.
4. Develop, quantify and validate scientific models of cell and tissue damage due to radiation at varying energy levels.
5. Develop noninvasive technologies to quantify radiation-induced damage to cells and tissues.

Other Considerations

The Canadian space physical science community has identified the following additional considerations related to broad scientific objectives, as requested by the CSA President at the beginning of the workshop. These include:

- building upon flight heritage
- leveraging and aligning with the academic community
- being adaptive and flexible to the international schedule
- aligning with the science and technology strategy and priorities of the Canadian government
- promoting improved international partnerships.

Physical science (or microgravity) experiments build upon flight heritage. These experiments date back to the early long-duration human spaceflights on Skylab in 1973. Experiments since include experiments on combustion, materials, fluids, protein crystal growth, fundamental physics, and technology demonstrations. Canadian physical science has also built on its flight heritage in most of these sub-disciplines through missions on near-free-fall platforms (such as drop towers; parabolic aircraft; sounding rockets; recoverable satellites; the Space Shuttle; the Mir Space Station and now the International Space Station).

The Canadian space physical science program has been leveraging the national academic community since 1984 through contracts leveraging funds from NSERC and Canadian industry. During this time, Canadian researchers have been involved in the experimental design, testing and qualification of science missions across the full range of sub-disciplines in space physical sciences. This effort has led to profound discoveries in reduced-gravity science, including quantifying the role of Marangoni (surface-tension) driven convection at the surface of an evaporating liquid, as well as the influence of gravity on contact angle.

Physical science experiments have been successfully adapted to international mission schedules. Experimental research in the near-free-fall environment has been largely dependent on access, resulting in large wait times between flight opportunities. This is true for experiments that have flown on human spaceflight missions (Shuttle, Soyuz) as well as sub-orbital rockets (2.5 year preparation time for a 7 to 14 minute flight) and recoverable satellites (2.5 year preparation time for a 14 to 17 day mission).

The international community adapted to schedule slips in preparing for these missions, as well as regular delays in ISS completion, by:

(a) further developing technology necessary to reach the community's scientific objectives
(b) planning additional parabolic flights, sub-orbital and recoverable satellite missions
(c) preparing for the next experiment and/or mission, depending on funding opportunities, and
(d) developing spin-offs for Canadians and transferring knowledge to directly assist Canadian industry.

Canada's first opportunity with repeatable experimentation was identified during the late 1990s with experiments onboard the Russian Mir Space Station. With the ISS nearing completion and its potential as a world-class orbiting near free-fall laboratory, the time has come for regular repeatable space physical science experiments.

The sub-disciplines of space physical science naturally map into the Government of Canada's Science and Technology Strategy and Priorities. The community's past experiments have directly addressed the government's priorities in energy, health, biotechnology, and information communication technologies (media).

The Canadian community has a strong interest in conducting near-free-fall experimentation. The Canadian program receives up to 50 proposals to CSA Announcement of Opportunities. These projects represent hundreds of highly qualified personnel and are aimed at maintaining and increasing Canada's recognized excellence in this field, as well as operational spaceflight experience.

Finally, the space physical science program has contributed to improved national and international partnerships over the years. The program has partnered on missions with NASA, ESA, JAXA, and Russia over the past twenty years. It cooperated with China for the first time on a recoverable satellite experiment in 2002. In 2005, it began preparing for future collaboration between CSA and the Chinese Space Agency.

Appendix I: CSEW6 Steering Committee

Editing committee:

Name	Title	Role
Dr V J Hipkin	Program Scientist, Planetary Exploration, CSA	CSEW6 Convenor
Prof. M. A. Dixon	Director, Controlled Environment Systems Research Facility, Chair, Environmental Biology Department, University of Guelph	CSEW6 Chair, Space Exploration Advisory Committee Chair
Prof. J. R. Drummond	Canada Research Chair, Remote Sounding of Atmospheres, Dalhousie University	
L. Dotto	Freelance science writer	
Prof. D Williams	Director, McMaster Centre for Medical Robotics, Professor of Surgery Department of Health Sciences, McMaster University	
Prof. R Pudritz	Director, Origins Institute, Professor, Dept. of Physics and Astronomy, McMaster University	

CSEW6 Co-chairs & Discipline leads:

M. Bamsey	PhD student, CSA/University of Guelph	Advanced Life Support
Dr M. Beech		Small bodies
Dr L. Cohen	Program Scientist, Space Life Sciences, CSA	Space Life Sciences
Dr M. Dejmek	Program Scientist, Space Physical Sciences, CSA	Space Physical Sciences
Prof M. A. Dixon	see above	Advanced Life Support
Prof J. R. Drummond	see above	Mars Atmosphere
Dr J Dupuis	Program Scientist, Space Astronomy, CSA	Space Astronomy
Dr A Ellery	Dept of Mechanical and Aerospace engineering, Carleton University	Astrobiology
Dr J Elliott	Canada Research Chair in Interfacial Thermodynamics, University of Alberta	Space Physical Sciences
Prof. D Hart	Dept of Microbiology and Infectious Diseases, University of Calgary	Space Life Sciences
Dr C Herd,	Dept of Earth and Atmospheric Science, University of Alberta	Astromaterials
Dr R. Herd	Curator, National Meteorite Collection of Canada, Geological Survey of Canada, NRCAN	Astromaterials
Prof P. Hickson	Dept of Astronomy & Astrophysics, University of British Columbia	Space Astronomy
Dr P Johnson-Green	Senior Program Scientist, Life and Physical Sciences, CSA	Space Life Sciences
Dr R. Léveillé	Visiting Fellow, Planetary Exploration, CSA	Astrobiology
Dr W. Liu	Program Scientist, Solar-terrestrial sciences, CSA	Solar-terrestrial science
Dr J Saary	University of Toronto and Defence Research and Development Canada	Operational Space Medicine
Dr P. Sullivan	Project officer, Operational Space Medicine, CSA	Operational Space Medicine
Prof P. Sylvester	Dept of Earth Sciences, Memorial University of Newfoundland	Planetary Geology & Geophysics
Prof A Waker,	Faculty of Energy Systems and Nuclear Science, UOIT	Radiation
Dr M-C. Williamson	Program Scientist, Planetary Exploration, CSA	Planetary Geology & Geophysics
Dr L. Whyte	Canada Research Chair in Environmental Microbiology, McGill University	Astrobiology
Prof A. Yau	NSERC/EMS/CSA/Bristol Industrial Research Chair in Experimental Space Science, University of Calgary	Solar-terrestrial science

CSEW6 organization:

L. Gilbert	Program assistant, Planetary Exploration & Space Astronomy , CSA
S. Girouard	Adminstrative clerk, Planetary Exploration & Space Astronomy, CSA

Dr D. Lacelle	Visiting Fellow, Planetary Exploration, CSA

Appendix II: Discipline Working Groups' Membership

Advanced Life Support

Dixon, M, chair	Guelph
Bamsey,M	Guelph
Bonin, G	Toronto
Braham, S	Simon Fraser
Chappell, L	MDA
Gosselin, A	Laval
Graham, T	Guelph
Lasseur, C	ESA
Rondeau Vuk, T	Guelph
Scott, A	Com Dev
Stasiak, M	Guelph
Wheeler, R	NASA KSC

Astrobiology

Whyte, L (chair)	McGill
Anderson, D	SETI
Banerjee, N	Western Ontario
Best, M	Victoria
Cloutis, E	Winnipeg
Dietrich, P	MDA
Dumas, S	Laval
Ellery, A	Carleton
Fought, J	Alberta
Fortin, D	Ottawa
Konnhauser, K	Alberta
Leveille, R	ASC/CSA
McKay, C	NASA Ames
Nadeau, J	McGill
Osinski, G	Western Ontario
Pollard, W	McGill
Pudritz, R	McMaster
Sherwood-Lollar, B	Toronto
Slater, G	McMaster
Southam, G	Western Ontario
Sapers, H	Western Ontario
Suttle, C	UBC
Vali, H	McGill
Wing, B	McGill

Astromaterials

Herd, C (Chair)	Alberta
Cloutis, E	Winnipeg
Davis, D	Toronto
Flemming, R	Western Ontario
Herd, R	NRCAN
Higgins, M	UQaChicoutimi
Hudon, P	McGill
Kissin, S	Lakehead
McCausland, P	Toronto
Nicklin, I	Royal Ontario Museum
Osinski, G	Western Ontario
Spooner, E	Toronto
Spray, J	UNB
Srinivasan, G	Toronto
Tait, K	Royal Ontarion Museum
Thomson, L	UNB
Wilson, G	Turnstone Geol. Services

Mars Atmosphere

Drummond, J. R (chair)	Dalhousie
Barnes, G	Routes
Bernath, P	Waterloo
Chesser, H	York
Conway, S	York
Duck, T	Dalhousie
Erkorkmaz, S	MDA
Gagne, M-E	York
Gafoor, N	MDA
Girard, T	Com Dev
Gordon, B	Routes
Hackett, J	Com Dev
Jones, D	Toronto
Kaminski, J	York
Lange, C	Alberta
LeBlanc, L	Dalhousie
LLewelyn, E	**Saskatchewan**
McConnell, J	York
Melo, S	ASC/CSA
Mohammad, F	York
Moreau, L	ABB
Pathak, J	York
Quine, B	York
Rahnama, P	Com Dev
Smith, K	Routes
Strong, K	Toronto
Taylor, P	York
Ward, W	UNB
Whiteway, J	York

Operational Space Medicine

Saary, J (chair)	Toronto
Brown, R	Vancouver General Hospital
Gaudet, A	Hopital Sacré Cœur Montreal
Hirsch, N	ASC/CSA
Lange, M	Ottawa
Lehnhardt, K	Western Ontario
Lim, D	Toronto
Musson, D	McMaster
Otto, C	Ottawa
Petrescu, N	Toronto
Saint-Jacques, D	Inuulitsivik Health Centre
Silverman, D	Toronto
Smith, M	Bubble Tech Industries
Stewart, G	Ottawa
Sullivan, P	ASC/CSA
Whelan, S	McMaster
Williams,D	McMaster

Planetary Geology & Geophysics

Sylvester, P (co-chair)	Memorial
Williamson, MC (co-chair)	ASC/CSA
Grasby, S	NRCAN
Heimpel, M	Alberta
Jellinek, M	UBC
Herd, R	NRCAN
McCausland, P	Western Ontario
Osinski, G	Western Ontario
Peterson, R	Queens
Rivard, B	Victoria
Samson, C	Carleton
Soare, R	Concordia

Stanley, S	Toronto
Therriault, A	NRCAN

Appendix III - CSEW6 Participant List (page 1 of 2)

Last Name	First Name	Organization
Abbasi	Viqar	ASC / CSA
Akingunola	Ayodeji	York Univ.
Ali	Mohamed	Univ. Toronto (UTIAS)
Antonenko	Irene	Univ. Western Ontario
Arkani-Hamed	Jafar	Univ. Toronto
Asquin	Donald	Routes AstroEngin.Ltd.
Auclair	Simon	Univ. Western Ontario
Bamsey	Matthew	ASC / CSA
Barfoot	Tim	Univ. Toronto (UTIAS)
Battler	Melissa	Univ. Western Ontario
Beauchamp	Louise	ASC / CSA
Bell	Andrew	Com Dev, Canada
Bellerose	Julie	JAXA / ISAS
Bergeron	Alain	INO
Berinstain	Alain	ASC / CSA
Binsted	Kim	Univ. Hawaii
Biren	Marc	Univ. New Brunswick
Boily	Jocelyn	AstroKeys Inc.
Bolger	James	MDA
Borra	Ermanno	Univ. Laval
Boucher	Dale	Norcat
Boudreault	Richard	Tech. Aérospatiales
Braham	Stephen	Simon Fraser Univ.
Bridge	Nathan	Univ. Western Ontario
Brown	Ross	Vancouver Gen. Hospital
Buckley	Nicole	ASC / CSA
Buckley	Robin	Dalhousie Univ.
Cantin	Daniel	INO
Carroll	Kieran	Gedex
Cavell	Ronald	Univ. Alberta - ISSET
Cloutis	Edward	Univ. Winnipeg
Cofsky	Sylvain	ASC / CSA
Daly	Mike	MDA Corporation
de Carufel	Guy	Univ. Toronto (UTIAS)
Dejmek	Marcus	ASC / CSA
Dempsey	Dale	CIHR
Dietrich	Peter	MDA
Dixon	Laura	Carleton Univ.
Dixon	Mike	Univ. Guelph
Draisey	Sherry	Good Vibrations Eng. Ltd
Drummond	James	Dalhousie Univ.
Dsouza	Ian	Com Dev, Canada
Dupuis	Erick	ASC / CSA
Dupuis	Jean	ASC / CSA
Dutil	Yvan	Univ. Laval
Ellery	Alex	Carleton Univ.
Elliott	Janet	Univ. Alberta
Eyer	Jesse	Univ. Toronto (UTIAS)
Faragalli	Michele	McGill Univ.
Fazekas	Andrew	SkyNews
Fazel-Rastgar	Farahnaz	York Univ.
Flemming	Roberta	Univ. Western Ontario
Forrest	Alexander	Univ. British Columbia
Fortier	Rejean	ASC / CSA
Fortin	Michel	INO
Fougères	André	INO
Furgale	Paul	Univ. Toronto (UTIAS)
Gagnon	Martin	Univ. Queb. Trois-Rivières
Gaudet	Adrienne	Hop. Sacré Cœur Montreal
Ghadaki	Farnaz	Univ. Toronto (ASX)
Ghafoor	Nadeem	MDA
Girard	Terry	Com Dev
Giroux	Jacques	ABB
Giroux	Richard	ASC / CSA
Gordon	Blair	Routes AstroEngineering
Graham	Thomas	Univ. Guelph
Grasby	Stephen	Geol. Survey Canada
Greene	Michael	Univ. Toronto (UTIAS)
Gulder	Omer	Univ.Toronto (UTIAS)
Gurtuna	Ozgur	Turquoise Tech. Sols Inc.
Haddad	Emile	MPB Comm. Inc.
Haltigin	Tim	McGill Univ.
Hart	David	Univ. Calgary
Heald	Johanne	ASC / CSA
Herd	Richard	NRCAN
Hickson	Paul	Univ. British Columbia
Hipkin	Victoria (Vicky)	ASC / CSA
Hirsch	Natalie	ASC / CSA
Huber	Kathleen	ASC / CSA
Hughson	Richard	Univ. Waterloo
Jagersand	Martin	Univ. Alberta
Jayarajah	Christine	Univ. Toronto
Johnson-Green	Perry	ASC / CSA
Jones	Brad	Neptec Design Group
Joyal	Jean-Sébastien	Hôpital Ste-Justine
Kaminski	Jacek	WxPrime Corporation
Kaspi	Vicky (Victoria)	ASC / CSA
Kaya	Tarik	Carleton Univ.
King	Geoffrey	McGill Univ.
Koujelev	Alexander	ASC / CSA
Kruzelecky	Roman	MPB Comms Inc.
Lacelle	Denis	ASC / CSA
Lai	Jeanie	ASC / CSA
Lange	Marvin	Univ. Ottawa
Laurin	Denis	ASC / CSA
Lay	Chih-Ying	McGill Univ.
Lebeuf	Martin	ASC / CSA
Lee	Pascal	Mars Institute
Legacey	Denis	Legacey Consulting
Lehnhardt	Kris	Univ. London, Health Sci Centre
Leshner	Rich	NASA
Léveillé	Richard	McGill Univ.
Levesque	Marc	INO
Lim	Darlene	NASA Ames Res. Centre
Lim	Dawn	Univ. Toronto
Lipsett	Mike	Univ. Alberta
Liu	William	ASC / CSA
Lovi	David	Univ. Alberta
Ma	Zhen Guo	Univ. Saskatchewan
Maag	Graeme	MDA
MacLeod	James	MDA
Mader	Marianne	ASC / CSA
Mah	Jason	Carleton Univ.
Mann	Ian	Univ. Alberta
Manuel	John	ASC / CSA
Marius-Phaneuf	René-Pier	ASC / CSA
Marsan	Bernard	ASC / CSA
Martin	Eric	ASC / CSA
Martinez	Jose	DigiSpace
Maszkiewicz	Michael	ASC / CSA
McCausland	Phil	Univ. Western Ontario
McConnell	John	York Univ.
McCullough	Emily	Univ. Western Ontario
Miles	David	Univ. Alberta
Mississian	Marina	Com Dev
Moffat	Brian	Com Dev
Moreau	Louis	ABB Bomem Inc.
Mulugeta	Lealem	Independent Researcher
Musson	David	McMaster Univ.
Naud	Marie-Ève	Université de Montreal
Negulic	Eric	Dalhousie Univ.
Niederberger	Thomas	McGill Univ.
Osinski	Gordon	Univ. Western Ontario
Otto	Christian	Univ. Ottawa
Ouellet	Alain	ASC / CSA

Palmieri	Benoit	ASC / CSA
Patel	Aabid	ASC / CSA

Appendix III - CSEW6 Participant List (page 2 of 2)

Last Name	**First Name**	**Organization**
Pearce	Geoffrey	Univ. Western Ontario
Peterson	Ron	Queen's Univ.
Petrescu	Nicolae	Univ. Toronto
Piontek	Derrick	Bristol / Magellan Aerospace
Pope	Tim	INO
Proulx	Antoine	INO
Quine	Brendan	York Univ.
Radtke	Kristin	McGill Univ.
Rankin	Robert	Univ. Alberta
Ravindran	Gita	MDA
Reid	Donnie	Vancouver Aquarium / PLRP
Renaud	James	ASC / CSA
Rhatigan	Jennifer.L.	NASA
Richard	James	Electric Vehicle Control Ltd.
Richards	Robert (Bob)	Optech
Rivard	Benoit	Univ. Victoria
Roberts	Caroline	Thoth Technology Inc.
Rocheleau	Simon Guy	Univ. Laval
Rondeau Vuk	Theresa	Univ. Guelph
Rowlands	Neil	Com Dev
Saary	Joan	Univ. Toronto
Saint-Jacques	David	Inuulitsivik Health Centre
Samson	Claire	Carleton Univ.
Sapers	Haley	Univ. Western Ontario
Scott	Al	Com Dev
Shademan	Azad	Univ. Alberta
Shah	Amee	Univ. Toronto (UTIAS)
Shepard	Rebekah	UC Davis
Sherwood Lollar	Barbara	Univ. Toronto
Shortt	Kevin	Canadian Space Society
Silverman	Greg	Univ. Toronto
Singleton	Alaura	Univ. Western Ontario
Smith	Charladean	ASC / CSA
Smith	Martin	Bubble Tech Industries
Soare	Richard	Concordia Univ.
Southam	Gordon	Univ. Western Ontario
Spencer	Henry	SP Systems
Spray	John	Univ. New Brunswick
Sterling	George	ASC / CSA
Stewart	Gregory	Univ. Ottawa
St-Maurice	Jean-Pierre	Univ. Saskatchewan
Stokan	Edward	Univ. Western Ontario
St-Pierre	Jean	L-3 MAPPS
Studd	Duncan	Carleton Univ.
Sullivan	Patrick	ASC / CSA
Sylvester	Paul	Memorial Univ.
Tanguay	Danielle	Trema Gestion Conseil Inc.
Tétreault	Martin	ASC / CSA
Thompson	Lucy	Univ. New Brunswick
Thomson	Laura	Univ. Western Ontario
Tomi	Leena	ASC / CSA
Trichtchenko	Larisa	NRCan
Urbain	Jean-Pierre	Science Presse
Vachon	Eric	ASC / CSA
Veillette	Dominic	Univ. Western Ontario
Waker	Anthony	Univ. Ontario Inst. Tech.
Ward	William	Univ. New Brunswick
Whelan	Sheila	McMaster Univ.
Whiteway	James	York Univ.
Whyte	Lyle	McGill Univ.
Wilhelm	Roland	McGill Univ.
Williams	David R.	McMaster Univ.
Williamson	Marie-Claude	ASC / CSA
Wing	Boswell	McGill Univ.
Wong	Julielynn	Univ. Pittsburgh
Wu	Di	York Univ.
Yau	Andrew	Univ. Calgary
Zee	Robert E.	Univ. Toronto (UTIAS)
Zwick	Harold	MDA