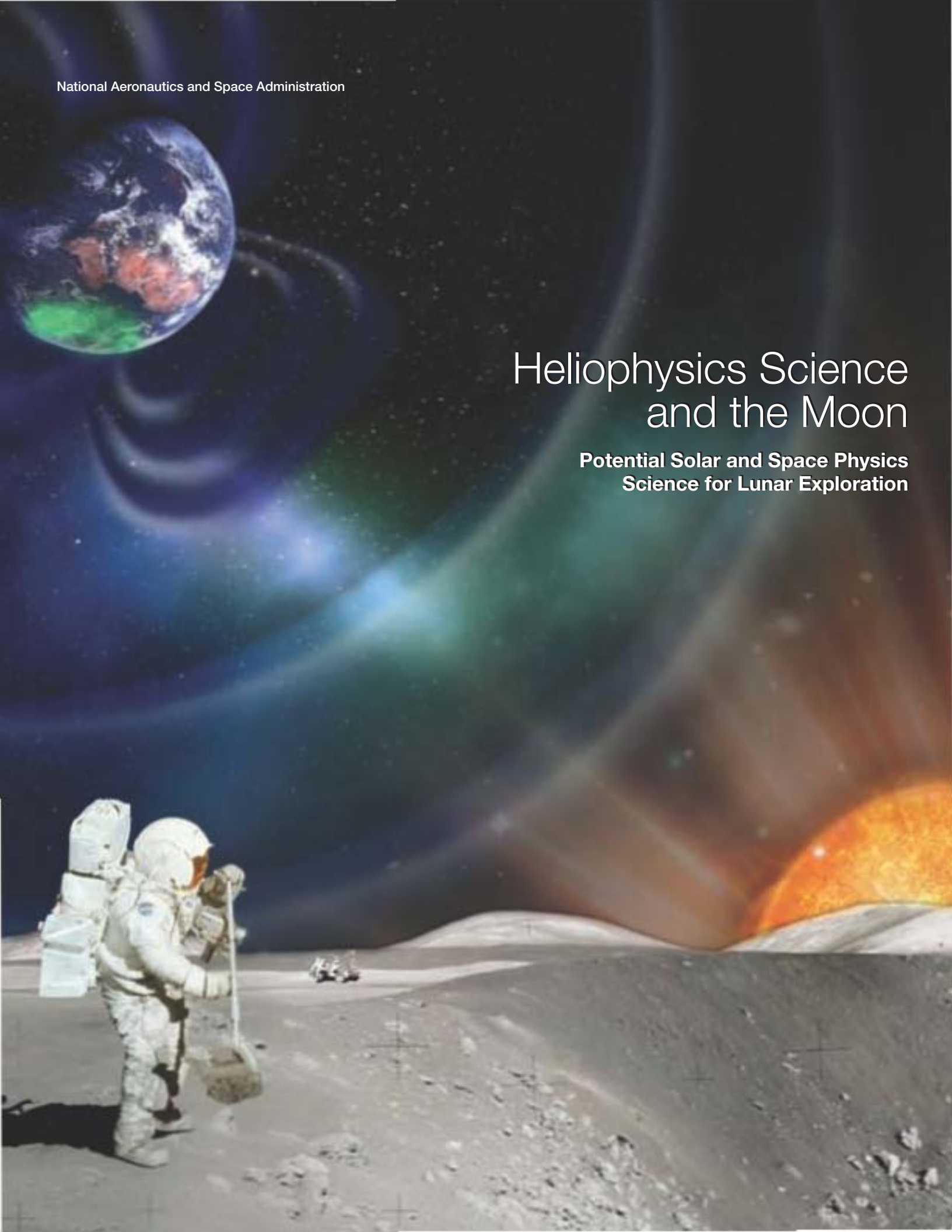National Aeronautics and Space Administration

Heliophysics Science and the Moon

Potential Solar and Space Physics Science for Lunar Exploration

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Subpanel for Heliophysics Science and the Moon

Report to the NASA Advisory
Council Heliophysics Subcommittee

September 2007

Heliophysics Subcommittee of the NASA Advisory Council

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Heritage of Heliophysics Science in Human Exploration

Since the inception of NASA, Solar and Space Physics have been an integral part of the Agency's science and human space flight program. Several historical vignettes that highlight the integration of Heliophysics science with a broad range of NASA activity are included throughout this report. These by themselves tell a powerful story of the role Solar and Space Physics have played in the evolution of the Agency. Together with the lunar science topics, they point to the significant role of Heliophysics in science and exploration of the Moon.

Introduction

The Moon is immersed in a plasma environment — the local cosmos — that is "magnetized." It is threaded with magnetic fields that are often "frozen" into the plasma, a state of high electrical conductivity that effectively couples the motions of the plasma and the magnetic field. This inherently strong coupling means that the structure and evolution of magnetic fields (of the Sun, of the Earth, and even of the Moon itself) play an essential role in organizing and regulating the local environment of the Moon — the environment to be experienced by our explorers. By working to understand, and so predict, the variations that occur from day to day, and from region to region, the productivity and overall success of future lunar robotic and manned missions can be significantly enhanced.

The most interesting challenge of the lunar plasma-field environment is that it is alternately dominated by the extended, but variable, outer atmosphere (the "magnetosphere") of the Earth and by the extended, but highly variable, atmosphere of the Sun (the "heliosphere"). The Moon spends nearly 25% of its orbital period immersed within the Earth's magnetosphere, which offers some degree of shielding from heliospheric effects; the remaining time is spent exposed to the full effects of the Sun's radiation and interplanetary fields. Thus, the lunar plasma environment offers unique opportunities to study a variety of fundamental plasma physics processes — processes that have application to many other objects throughout the universe.

Since the inception of the U.S. space program with Explorer 1, and continuing through to present space weather missions, scientists in the heliophysics community have worked to develop a thorough understanding of the connected Sun-Earth-Moon system. A great deal more is known about our space environment than was known during the Apollo era, and this new knowledge is ready to be applied. Data from heliophysics missions, past and present, can be mined for applicable measurements. Our understanding of underlying physical processes can be used to provide an informed predictive capability that will aid in the operational planning for lunar and eventually Mars missions. The Heliophysics Great Observatory (an ensemble of spacecraft designed to provide system measurements of the Sun-Earth system) is available to provide real-time space weather awareness during manned flights. And, once a manned presence on the Moon has been achieved, new classes of experiments can be implemented to further advance these fields of study.

Heliophysics science therefore plays two distinct complementary roles within the framework of the Vision for Space Exploration; Meaningful advances in our scientific understanding of basic plasma science will be realized by the era of lunar exploration, and a greater understanding of heliophysics science will be a critical enabling component for the exploration initiative.

This report addresses both these features—new science enabled by NASA's exploration initiative and enabling science that is critical to ensuring a safe return to the Moon and onward to Mars.

The areas of interest are structured into four main themes:

Theme 1:
Heliophysics Science of the Moon
Studies of the Moon's unique magnetodynamic plasma environment.

Theme 2:
Space Weather, Safeguarding the Journey
Studies aimed at developing a predictive capability for space weather hazards.

Theme 3:
The Moon as a Historical Record
Studies of the variation of the lunar regolith to uncover the history of the Sun, solar system, local interstellar medium, galaxy, and universe.

Theme 4:
The Moon as a Heliophysics Science Platform
Using the unique environment of the lunar surface as a platform to provide observations beneficial to advancing heliophysics science.

The heliophysics science community has a long history of synergism with NASA's manned flight program. Examples include the early Explorer program, which discovered the ubiquitous nature of trapped radiation within Earth's space environment; the Apollo program, which conducted many heliophysics-related science experiments; the deployment of solar and space physics instrumentation on Skylab; the use of space plasma instrumentation to document the space environment of the Space Shuttle; and the development of space climate corrections for operational atmospheric drag and

communication error models. The advent of NASA's 21st century exploration initiative offers exciting new opportunities for further synergism between these communities.

In February 2007 a group of approximately twenty experts on solar and space physics met as part of a workshop at the Fiesta Inn Resort conference facilities in Tempe, Arizona. At this workshop, sponsored by the NASA Advisory Council and its Science Subcommittees, recommendations from the scientific community for science associated with the return to the Moon were presented, discussed, and distilled into a series of scientific objectives, each with specific science goals and benefits, and implementation considerations. For concise presentation, see Spence, 2007. This report provides a synopsis of these objectives. Each of these objectives is further organized into a number of subsections, covering:

1. A summary of the science objective;

2. The value of the investigation, both to scientific research and to developing an enhanced predictive capability of space weather hazards;

3. An expanded discussion of the science objective;

4. A description of the required instrumentation and its deployment mode(s);

5. A discussion of the extent to which astronaut involvement is necessary/desirable;

6. A discussion of the wider benefits, both to other areas of science and to safeguarding missions to the Moon and Mars.

The science objectives articulated in this report will not only extend our comprehension of basic plasma interactions and the coupling of complex regions throughout the heliosphere, but also further our knowledge of the history and evolution of our "little corner" of the universe with greatly expanded observations. This is in addition to providing foundational understanding of the "perilous ocean" which spacefaring spacecraft and crews must traverse in order to reach their destinations within the solar system.

It should be noted that while the science objectives contained in this report have been considered and reviewed by many solar and space physics scientists, they have not been vetted or prioritized through the established and robust process of a community-based roadmap or decadal survey.

Heliophysics Science of the Moon

• Characterize the Near-Lunar Electromagnetic and Plasma Environment

• Map and Determine the Origins of the Moon's Remanent Crustal Magnetic Fields

• Magnetotail Dynamics at Lunar Orbit

• Interaction of Plasmas with the Moon

• Characterize and Understand the Interaction of Dust and Plasma on the Surface of the Moon and in the Lunar Exosphere

Introduction

In our quest to understand our space environment, our first challenge is to understand the basic physics behind the plasma processes of magnetic reconnection, the mass loading of solar and stellar winds, and plasma-dust interactions. These processes play fundamental roles in the explosive processes at the Sun, and in planetary accretion. Increasingly, as we probe more deeply into the underlying plasma-field interactions, heliophysicists are guided by comparisons of plasma processes in the Earth's magnetosphere, in the solar corona, in the magnetospheres of other bodies in the solar system (the Moon and planets), and in distant astrophysical environments. This comparative approach creates a rich variety of unique opportunities for lunar-based heliophysics science.

Explorer 1 Discovery of Space Radiation

"James Van Allen was one of the greatest and most accomplished American space scientists of our time and few researchers had such wide range of expertise in so many scientific disciplines," said NASA Administrator Michael Griffin. "NASA's path of space exploration is far more advanced today because of Dr. Van Allen's ground breaking work." Van Allen's most widely known contribution was the 1958 discovery of radiation belts, now called Van Allen belts, encircling the Earth. He also is credited with discovery of a new moon of Saturn in 1979, as well as radiation belts around that planet.

The three men responsible for the success of Explorer 1, America's first satellite, launched Jan. 31, 1958. From left, William H. Pickering, James Van Allen, and Wernher von Braun.

The areas of interest all exploit the Moon's unique magnetodynamic environment:

• The Moon has weak crustal magnetic fields, the origin of which is still a mystery and a central question for the science of the Moon. These weak magnetic fields continually interact with the solar wind and with lunar dust very close to the lunar surface. The presence of weak magnetic fields is common to many planetary bodies, including Mars. On the Moon, however, the locations of these small-scale interactions can be identified precisely and studied near the lunar surface. This is a unique circumstance that will provide new insights into the fundamental behavior of magnetodynamic systems, and may hold lessons for models of magnetic fields in the Sun's corona, Earth's magnetosphere, and other planetary systems;

• As the Moon orbits the Earth, it passes through a rich variety of plasma environments that offer the opportunity to study plasma physics processes over a wide range of ambient conditions;

• Mass loading is a term describing the basic plasma process where bodies such as comets, planets, and moons produce dust and charged particles that become entrained in the impinging solar wind. We often observe the products of such interactions and their effects on the solar wind and other astrophysical or planetary plasmas. The lunar surface offers a unique location in which to study this process as it begins. These studies will contribute to many areas in space science and astrophysics, where the interaction with plasmas, dust, and charged particles plays a central role;

• Understanding the interaction of sub-micron lunar dust grains and the near-surface plasma is key to characterizing the lunar surface environment and associated potential hazards in which robotic and human explorers will operate. Studies on the Moon will include an investigation of interactions between charged particles and lunar dust.

The proposed investigations will therefore not only advance our characterization of the basic plasma interactions, key to an increased understanding of the organization and evolution of large-scale magnetodynamic systems, but will also inform key aspects of future plans for planetary exploration.

1.1 Characterize the Near-Lunar Electromagnetic and Plasma Environment

Summary

Interaction with the ambient plasma and incident solar ultraviolet (UV) radiation causes the lunar surface to become electrically charged (Manka, 1973; Stubbs et al., 2007a). This creates different and complex environments on the sunlit and shadowed side of the Moon. On the dayside, photoelectric processes driven by solar UV radiation typically dominate, so that the surface becomes positively charged (Singer and Walker, 1962). On the nightside, interactions with ambient plasma electrons usually dominate, leading to the surface acquiring a negative charge (Halekas et al., 2002). This interaction is complicated by variations in solar UV intensity, the characteristics of the ambient plasma, surface composition and topology, magnetic anomalies and the lunar wake, and by the formation of dusty plasmas. In general, the surface electric potential is confined to a near-surface sheath region. The vertical extent of this region, which is controlled largely by the ambient plasma density and temperature, in turn determines the surface electric field strength (Nitter et al., 1998).

Value

Surface charging is a fundamental universal process affecting all airless regolith-covered bodies, and it is believed to drive the transport of micron-scale dust, a recognized potential hazard for operations on the lunar surface (Stubbs et al., 2007b). In addition, differential charging of objects on the surface could lead to unanticipated electrical discharges. Understanding the electromagnetic/plasma environment near the lunar surface will therefore be of benefit both to manned and robotic surface exploration activities and to scientific investigations conducted on the lunar surface.

Description

Like any object immersed in a plasma, the surface of the Moon charges to an electric potential such that the total incident current is zero (Whipple, 1981). The charging currents come from four main sources: (1) photoemission of electrons, (2) plasma electrons, (3) plasma ions, and (4) secondary electrons (arising from surface ionization by plasma electrons). Due to photoionization by solar UV radiation, the lunar dayside typically charges to a few volts positive with a "photoelectron sheath" extending to ~1 m in altitude (Freeman and Ibrahim, 1975). On the nightside, however, interaction with the charged particles in the solar wind leads to surface charging to several hundred volts negative, with a "Debye sheath" extending up to ~1 km in altitude (Halekas et al., 2003). This basic picture comes from application of basic plasma theory to Apollo era and Lunar Prospector observations.

There remain significant uncertainties in lunar surface charging processes, and relatively little is known about either spatial or temporal variations in the charge density, electric potential, or field strength. Lunar surface charging in the solar wind is complicated by variations in the solar spectrum, in the ambient plasma environment, in surface composition and topography, by magnetic anomalies, and by the formation of a lunar wake and dusty plasmas. In addition to these effects, when the Moon passes nightside of the Earth, it traverses the tail lobes and plasma sheet of the Earth's magnetosphere. The plasma sheet is much more tenuous and significantly hotter than the solar wind, and observations from Lunar Prospector indicate that nightside potentials can reach a few thousands of volts (negative), both during space weather events and during plasma sheet passages (Halekas et al., 2007).

Surface charging processes may be a major driver of the transport of charged dust (e.g., Stubbs et al., 2007b), as observed during the Apollo era (also see section 1.5). The most probable mechanism for dust transport involves the like-charged surface and small (<10 micron) dust grains acting to repel each other. Hazards could arise both due to the differential charging of surface equipment, resulting in unanticipated electrical discharges, and to the transport of charged dust with its adhesive and abrasive properties. Since the lunar surface is an insulator, finding a common ground for electrical systems is much more difficult than on Earth.

Methodology and Instrumentation

The necessary in situ measurements for characterizing the near lunar plasma environment are summarized in the table below.

Instrument Package	Mass	Power	Telemetry Rate	Heritage
Electron and Ion Spectrometers	3 kg	5 W	30–500 kbps	Wind
Electric Field Probes	3 kg	1 W	0.5–1.0 kbps	ACE
Magnetometers	0.5 kg	1 W	1 kbps	Wind
Solar UV Spectrometers	0.5 kg	2 W	10 Mbps	SoHO
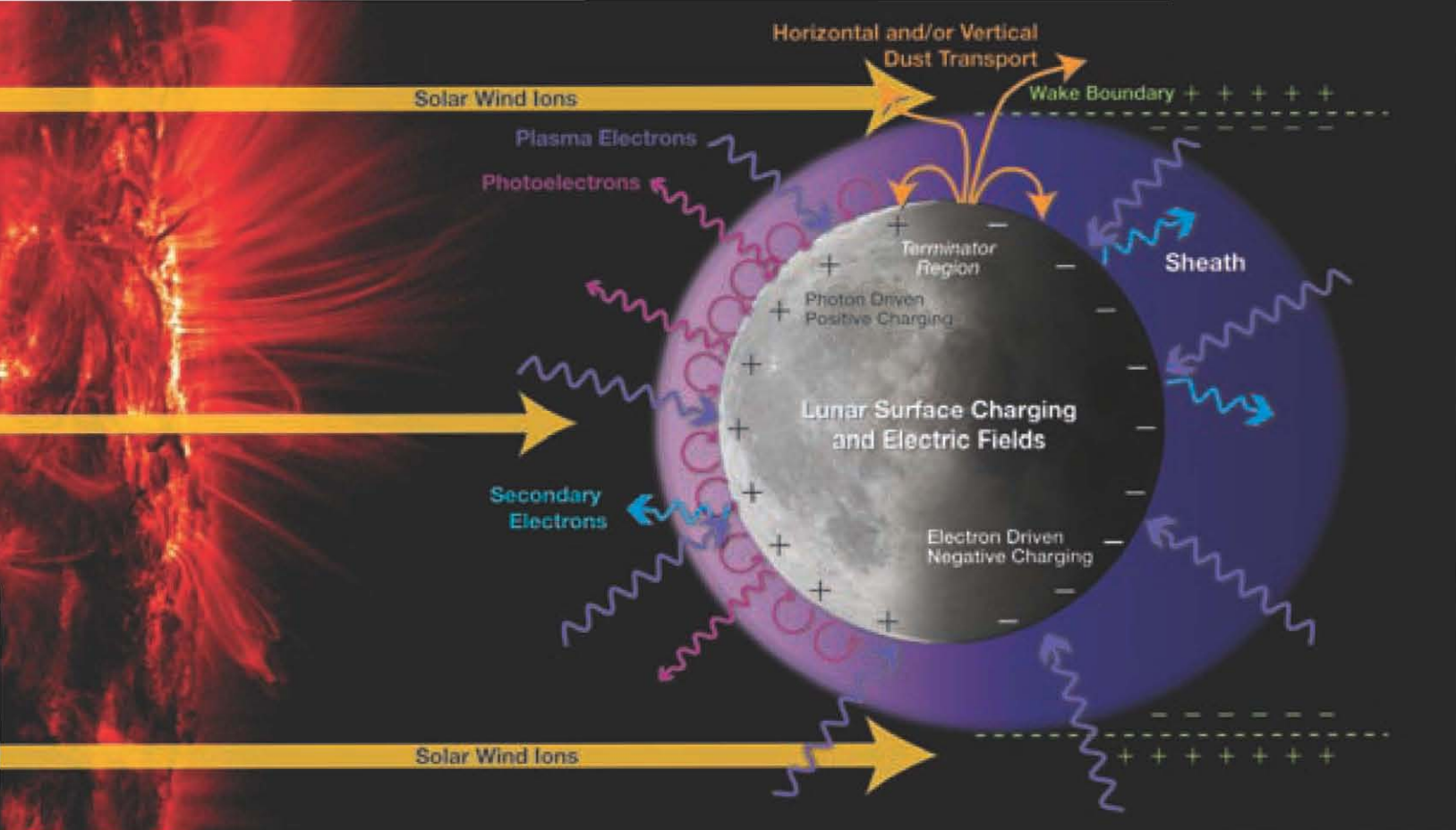
Schematic showing various lunar and solar wind plasma interactions (courtesy of University of California at Berkeley and Goddard Space Flight Center).

Observations can be carried out both from orbit (providing a global-scale view) or from the surface (providing a complementary local view). To optimize the characterization of the lunar plasma environment, it is recommended that measurements from orbit and the surface be coordinated, so that the connection between processes on different scales is understood. Not every point on the lunar surface experiences the same conditions; for example, locations near the poles will be quite different from those nearer the equator. Hence, it is advantageous to deploy surface-based instrumentation over a wide range of lunar sites.

The instruments described above all have a high Technology Readiness Level (TRL), with many of them being standard on past and existing heliophysics and planetary missions. Requirements for mass, power, and telemetry are all modest.

Extent of Astronaut Involvement

Astronauts could distribute a network of sensors on the lunar surface. In addition to measuring the natural environment, the instrumentation described above will also detect the charge on the astronauts themselves, revealing how astronauts and equipment are coupled to the local plasma environment.

Wider Benefits

The characterization of the lunar electromagnetic/plasma environment, and the resulting development of dust mitigation technology, permits a sustainable exploration program requiring surface operations, particularly astronaut extra-vehicular activities (EVAs). This study impacts other lunar science activities (e.g., Earth observation, astronomy, and astrophysics), environmental characterization, and operational environmental monitoring. It also paves the way for future missions, for In Situ Resource Utilization (ISRU) activities, and ultimately for the commercialization of the Moon.

Measurements of the lunar natural environment from orbit and from the surface

Continue monitoring of natural environment background and impact of surface operations

Deploy large-scale surface network to monitor and make predictions

1.2 Map and Determine the Origins of the Moon's Remanent Crustal Magnetic Fields

Summary
The discovery of lunar magnetism was a major scientific surprise of the Apollo program. Solving the enigmas of this remanent field will provide fundamental insights into the thermal history of the lunar core/dynamo and crust, and into the processes of magnetization and demagnetization in large basin-forming impacts. This will require systematic high-resolution mapping of crustal magnetic fields from orbit, surface magnetometer surveys of select regions, and the return of oriented samples.

Value
Lunar magnetism provides a powerful tool for probing the thermal evolution of the Moon's crust, interior, and core, as well as illuminating the physics of large basin-forming impacts. Insights into the lunar field will certainly help us understand Mars, which exhibits similar but much stronger crustal magnetism. The same processes will likely apply to other terrestrial bodies and to impact processes in general. Determining the distribution and properties of strong magnetic anomalies will clarify the potential magnetic shielding benefits for lunar bases.

Description
The Moon does not have an active core dynamo. However, like Mars, it has numerous localized remanent crustal magnetic regions distributed over its surface, with a spatial scale of a few kilometers well below the solar wind thermal ion gyro-diameter, to a few hundred kilometers, large enough to produce shocks for some solar wind conditions (Colburn et al.,1971; Russell and Lichtenstein, 1975; Lin et al., 1998; Halekas et al., 2006). The existence of these regions points to the presence of strong magnetizing fields in the past (Hood et al., 2001; Halekas et al., 2001).

Measurements of remanent magnetism on the Earth provided crucial evidence for sea floor spreading and plate tectonics that led to a greatly increased understanding of the evolution of the Earth's interior and surface. New measurements of lunar and Martian magnetism hold similar promise. Low-resolution orbital mapping by the Apollo 15 and 16 subsatellites and by Lunar Prospector using magnetometers and electron reflectometers shows strong surface magnetic fields in regions antipodal to the large impact basins formed ~3.65–3.85 billion years ago and in some of the ejecta from those impacts. At the same time, the basins themselves are at best weakly magnetized, suggesting that the antipodal magnetism results from shock remanent magnetization (SRM), possibly together with amplification of ambient magnetic fields by plasma produced in the impact process (Lin et al., 1988; Hood et al., 1991, 2001).

However, other evidence indicates a quite different source of the lunar magnetic field. Measurements of Apollo lunar samples suggest thermal remanent magnetization acquired in a strong (of order ~1 Gauss) core dynamo magnetic field during the same era (Fuller, 1974).

Resolving these puzzles and understanding the origins of lunar magnetism would provide the basis for unraveling the thermal history of the lunar core/dynamo and crust, as well as the physics of basin-forming impacts. Both these effects are likely to be important for Mars as well.

Methodology and Instrumentation
A focused three-part program, including targeted near-surface, high-resolution orbital measurements, surface magnetometer traverses, and laboratory analysis of oriented samples, would allow a determination of the properties of surface crustal remanent magnetization. Knowing the mode of remanent field acquisition (shock, thermal, etc.), and its strength, age, direction, coherence, and spatial scale would allow us to understand the physics of crustal magnetization and the magnetic history of the Moon. Initially, a small lunar-orbiting spacecraft with magnetometers and electron reflectometers would provide high spatial resolution mapping of the intensity and orientation of the crustal field by targeting low periselenes (less than ~15 km) over the key South Pole Aitken region and encompassing the strongly magnetized regions antipodal to the Crisium, Imbrium, and Serenitatis basins. Preferably the spacecraft would also measure the nearby demagnetized Orientale basin and two basins with central magnetic anomalies: Moscoviense and Mendel-Rydberg. These measurements would be compared with surface geology in order to constrain the age distribution of crustal magnetism and to quantify its relationship with impact basins, ejecta, and antipodal regions. Later, robotic rovers or humans would conduct magnetometer traverses over selected surface locations. Finally, oriented samples from cores or deep craters would be returned from key antipodal regions, mare basalts, magnetized ejecta, and large impact basins for analysis.
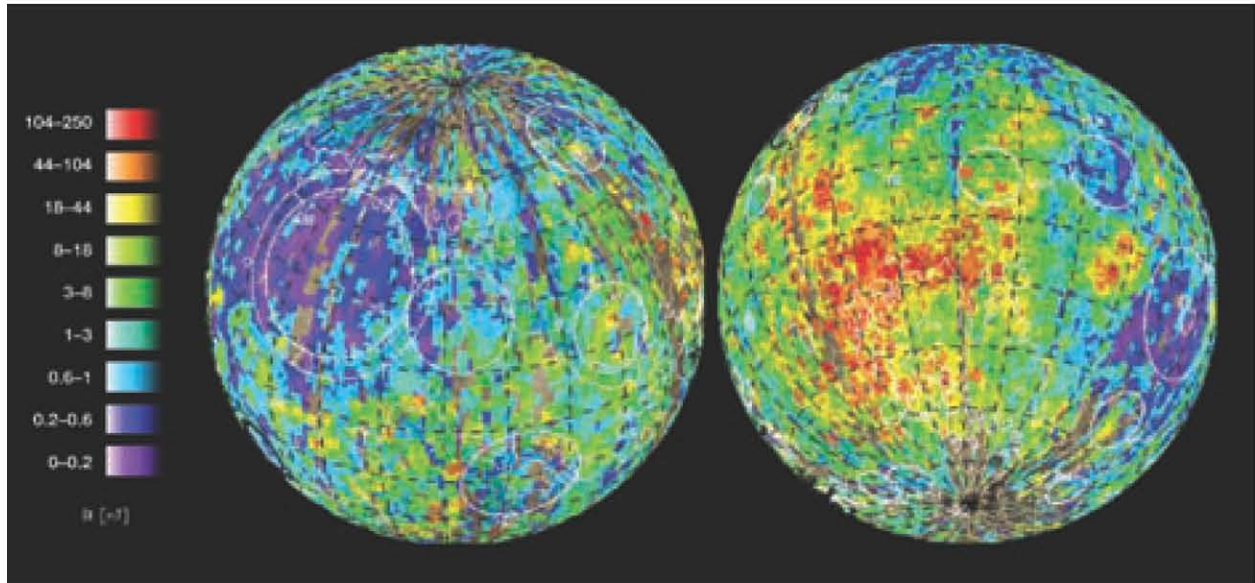
A map of the remanent lunar magnetic field strength measured by electron reflectometry from the Lunar Prospector mission. The field ranges from near 0 to 100 nT. Many strong concentrations appear at the antipodes of large lunar basins where the field is very weak.

An orbiting spacecraft with low periselene would employ a subset of the instrumentation essential for achieving the space weather and dust-plasma objectives:

Full 3-D Plasma Ion and Electron Sensors	3 kg	3 W	0.5–2 kbps	THEMIS
Magnetometer	1 kg	1 W	0.2–1 kbps	THEMIS

Surface traverse measurements would be conducted by rover-mounted magnetometers and/or astronauts with hand-held magnetometers, and carefully selected and well-documented oriented samples obtained by astronauts or by robots would be returned for Earth analysis.

Extent of Astronaut Involvement

Astronaut involvement would be very useful for surface magnetometer traverses and likely essential for oriented sample returns.

Wider Benefits

Many strong crustal magnetic anomalies are correlated with surface albedo markings, or "swirls." This strongly suggests that these larger, more intense field regions act as mini-magnetospheres that effectively shield the surface from solar wind ions, and thus may be relevant for lunar base site selection. Furthermore, these varied regions provide fixed plasma laboratories that will allow us to explore interesting and fundamentally different parameter regimes (see Theme 1.1).
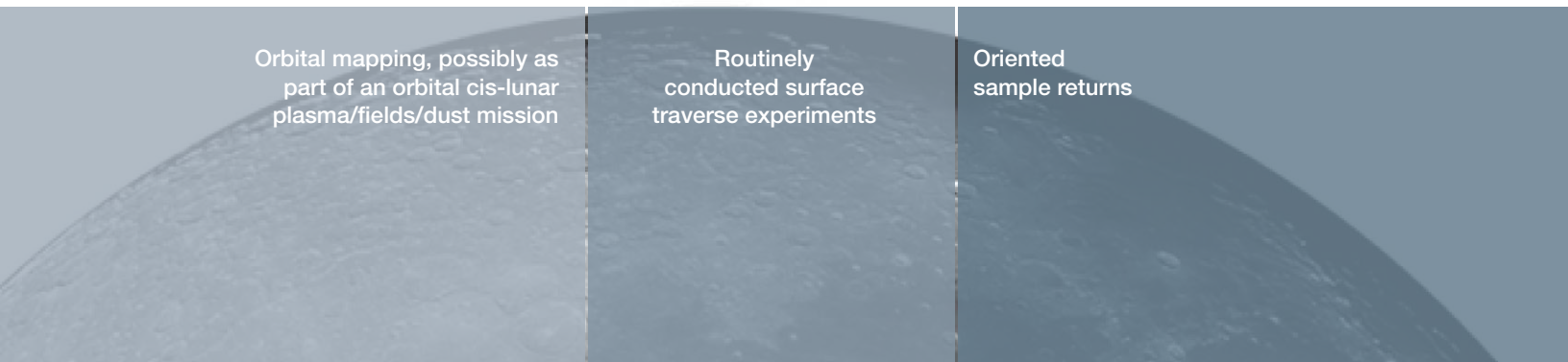
Orbital mapping, possibly as part of an orbital cis-lunar plasma/fields/dust mission

Routinely conducted surface traverse experiments

Oriented sample returns

1.3 Magnetotail Dynamics at Lunar Orbit

Summary

The dynamical behavior of the Earth's distant magneto-tail, where about half of the total energy coupled into the magnetosphere from the solar wind is stored, is completely different from the near-Earth [<30 Earth radii (Re)] tail and is presently not understood. Magnetic reconnection occurs nearly continuously in the distant magnetotail and the reconnection process there is fundamentally different from what occurs elsewhere. Observations around the Moon as it traverses the Earth's distant magnetotail have unique advantages for understanding the physics of this essentially unexplored and poorly understood region.

Value

The study of magnetic reconnection in the lunar environment is an exciting new research area for fundamental plasma physics and magnetospheric physics. Lunar shadowing of ambient electrons also provides a unique and powerful probe of the topology and convection velocity of magnetic fields. Finally, observations at lunar orbit are ideal for studying the dynamics of plasmoids that travel down the Earth's magnetotail after a substorm occurs closer to the Earth.

Description

The energy coupled from the solar wind into the Earth's magnetosphere goes primarily into the formation of a long (>200 Re) magnetotail. In the near-Earth magnetotail (<30 Re), the stored energy is released in transient substorms, but the distant tail undergoes near-continuous magnetic reconnection. Thus, despite the sparse spacecraft coverage, the Earth's magnetotail provides some of the best measurements possible of the reconnection process (Øieroset et al., 2001, 2002). Magnetic reconnection in the distant magnetotail is physically different (Egedal et al., 2005) from that which occurs in other environments, and it
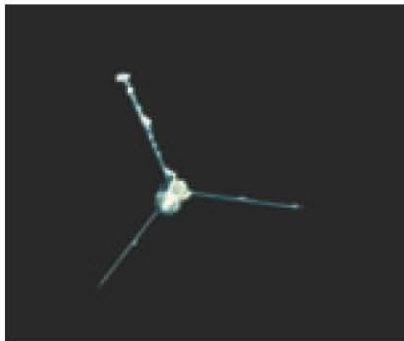
A 60-kg subsatellite ejected from Apollo 15 just before returning to Earth.

Apollo Subsatellite Measurement of the Space Plasma Environment

The Apollo 15 and 16 subsatellites (picture from a film taken of the deployment) were dropped off before the astronauts returned to Earth. They made the first measurements of the convection velocities of magnetic fields in the Earth's magnetotail by using the Moon to shadow fast electrons. They also detected and mapped hundreds of patches of magnetic fields on the Moon's surface (whose origins are still an enigma) through the serendipitous discovery of electron reflection magnetometry, a new technique for remote sensing and mapping of planetary magnetic fields surfaces.

is associated with the acceleration of electrons to energies of hundreds of kiloelectron volts (similar to what is observed for solar flares). Observations in the lunar environment thus provide a probe for fundamental plasma physics and magnetospheric physics. In addition, lunar shadowing of ambient electrons provides a unique and powerful probe of the topology and convection velocity of magnetic fields (McCoy et al., 1975; Lin et al., 1977). The Moon spends ~5 days each month crossing the distant magnetotail, enabling the extensive observations needed to understand the physics. Observations at lunar orbit should also be ideal for studying the dynamics of plasmoids that travel down the Earth's magnetotail after a substorm occurs closer to the Earth.

Methodology and Implementation
Initial studies would involve detailed plasma, energetic particle, and electric and magnetic field measurements by one or more lunar polar orbiting spacecraft to use lunar shadowing of electrons to uniquely determine magnetic topology and field line velocities. Later studies involve arrays of detectors or multiple orbiters at different spatial locations to look at small-scale structures in the plasma. In the long term, the release of barium clouds may be used to trace the plasma flows.

A complete set of plasma and field instrumentation for an orbiter (perhaps as a drop-off from an Apollo-like Science Instrument Module) would include:

Ion and Electron Electrostatic Analyzers	4 kg	3 W	200 bps	Wind
Ion Composition	5 kg	8 W	200 bps	FAST
Energetic Ions and Electrons	1.5 kg	1.7 W	200 bps	Wind
Magnetometer Boom and Sensor	3 kg	1 W	200 bps	THEMIS
E-field Booms and Sensors	15 kg	8 W	200 bps	THEMIS

*High data rate burst mode for transient events, stored in memory

Modified versions of the particle and field sensors with similar resources could also be used on ground packages.

Extent of Astronaut Involvement
Orbiters neither require nor benefit from astronaut involvement. For ground-based packages, astronaut involvement could simplify deployment and troubleshooting. The release experiments would involve visual observations from the Moon, and would best be done with astronaut involvement.

Wider Benefits
The proposed instrument complement would also be useful for crustal magnetism (1.2), Moon-plasma (1.4), and dust-plasma interaction (1.5) objectives. The ion composition experiment could also be used to make measurements of the lunar exosphere.

Lunar orbiters, perhaps dropped off into orbit on early cargo or human transport vehicles (cf. Apollo 15 & 16 subsatellites)

Deployment of ground-based packages

Ion releases from a platform on the lunar surface

1.4 Interaction of Plasmas with the Moon

Summary

The behavior of collisionless plasmas at the transition from kinetic (particle) to fluid scales is a research topic of fundamental importance in plasma physics, especially for astrophysical plasmas. The Moon has numerous regions of lunar surface magnetic fields of differing sizes spanning the kinetic to fluid scales, while cis-lunar plasmas span a wide range of physical parameters. Probing these near- and cis-lunar plasma environments permits studies of fundamental plasma physics at the kinetic/fluid interface.

Value

The Moon is uniquely suited for these studies — the solar wind, magnetosheath, and magnetotail provide a wide range of plasma conditions where there is little or no atmosphere. Since the locations of the magnetic regions are known a priori, they can be used as laboratories. Fundamental collisionless plasma processes, many inaccessible to ground-based facilities, can be investigated using the Moon.

Image of atomic oxygen glow of the Space Shuttle tail with the radiant blue aurora in the background.

Hazards of Atomic Oxygen Discovered in Low Earth Orbit

Atomic oxygen (O) and nitrogen (N) atoms are so reactive that they are rarely found by themselves in the high density environments near the Earth's surface. Even the familiar oxygen and nitrogen gas we breathe is composed of diatomic O_2 and N_2 molecules because the single atoms quickly combine to form the more stable molecules. The situation is quite different at ISS altitudes. Energy absorbed by the diatomic molecules from interactions with solar ultraviolet photons break the bonds holding the molecules together and the newly formed atomic species have very little chance to react with other atoms to recombine into diatomic molecules in the low density environment of low Earth orbit (LEO).

ISS designers — or anyone building spacecraft for operation in LEO — must carefully consider the atomic oxygen environment when selecting materials for use on the outer surfaces of spacecraft exposed to the space environment. Reactions with the corrosive atomic oxygen atoms will erode many materials, including a number of polymers, mirror coatings, and other spacecraft components.
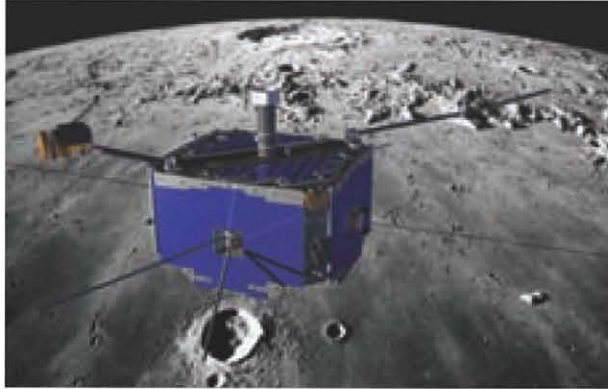
Artist's conception of a small satellite mission to investigate plasma interactions on the Moon.

Description

The interaction of solar wind, magnetosheath, and magnetotail plasmas with the Moon is important for fundamental (space) plasma physics studies. First, the Moon has numerous patches of surface magnetic fields, ranging in size from kilometer scale, well below the solar wind thermal ion gyro-diameter, to hundreds of kilometers, large enough to produce fluid magnetohydrodynamic (MHD) behavior (Colburn et al., 1971; Russell and Lichtenstein 1975; Lin et al., 1998; Halekas et al., 2005b). Thus, studies of the plasma interactions with these magnetic patches allow us to explore the fundamental physics of the transition from kinetic to fluid (MHD) scales and the related phenomena of shock formation. The Moon appears to be the only place where we can conduct these studies. In the plasma interactions with crustal fields, the ions decouple from the magnetic field first (an ion diffusion region) because of their much larger gyroradii, and then (depending on crustal field scale size) the electrons may also decouple. This behavior is thought to be similar to many fundamental collisionless plasma phenomena, such as magnetic reconnection, magnetopause, and shock formation.

Second, the solar wind colliding with the Moon produces a cavity behind the Moon. However, electrons traveling along the magnetic field (generally not parallel to the solar wind) can enter this cavity, generating very large charge separation electric fields in the process (Ogilvie et al., 1996; Halekas et al., 2005b), as well as a variety of plasma waves and beams.

Methodology and Instrumentation

Studies would involve plasma, fields, and energetic particle measurements from orbiters and/or on the lunar surface. A complete set of plasma and field instrumentation for an orbiter would include the following:

Ion and Electron Electrostatic Analyzers	4 kg	3 W	200 bps	Wind
Ion Composition	5 kg	8 W	200 bps	FAST
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*High data rate burst mode for transient events, stored in memory

Modified versions of the particle and field sensors with similar resources could also be used on ground packages.

Extent of Astronaut Involvement

The orbiters neither require nor benefit from astronaut involvement (but they could be dropped off from a manned mission). For ground-based packages, astronaut involvement could simplify deployment and troubleshooting, but is not required.

Wider Benefits

The instrument package above would also be useful for the crustal magnetism (1.2), magnetotail dynamics (1.3), and dust-plasma (1.5) objectives.

Lunar orbiters, perhaps dropped off into orbit on early cargo or human transport vehicles (cf. Apollo 15 & 16 subsatellites)

Deployment of ground-based packages

1.5 Characterize and Understand the Interaction of Dust and Plasma on the Surface of the Moon and in the Lunar Exosphere

Summary

The ambient plasma environment and solar UV at the Moon cause the regolith on the lunar surface to become electrically charged (Manka, 1973; Stubbs et al., 2007a). This can result in the electrostatic transport of charged dust (<10 μm) in the lunar exosphere, which has been observed to reach altitudes >100 km (McCoy and Criswell, 1974; McCoy, 1976; Zook and McCoy, 1991) and speeds of up to 1 km/s (Berg et al., 1976). However, the dominant mechanisms that drive this behavior are unknown.

Value

From the Apollo era it is known that dust will have an immediate impact on surface exploration activities and must be addressed to ensure mission success (Bean et al., 1970; Goodwin, 2002). During Apollo, electrostatic processes are thought to have increased the problems with dust, such as adhesion to suits and equipment (Stubbs et al., 2007b). Characterizing the surface electric field and the electrostatically transported dust's grain size, charge, and spatial distribution, as well as the perturbation of man-made structures to these measurements, is required to provide an understanding of the lunar dust-plasma environment and its impact.

Apollo 17 Astronaut Gene Cernan in Lunar Module covered in lunar dust after walking on the Moon.

Description

During the Apollo era it was discovered that sunlight was scattered at the lunar terminator, giving rise to "horizon glow" and "streamers" above the surface (e.g., McCoy and Criswell, 1974). This scattering is most likely caused by electrically charged dust grains originating from the surface (Zook and McCoy, 1991; Rennilson and Criswell, 1974). The lunar surface is electrically charged by the local plasma environment and the photoemission of electrons by solar UV, as discussed in section 1.1.

Under certain conditions, the like-charged surface and dust grains act to repel each other, thus transporting the dust grains away from the surface. The limited observations of this phenomenon, together with laboratory and theoretical work, suggest that there are two modes of charged dust transport: "levitation" (Sickafoose et al., 2002) and "lofting" (Stubbs et al., 2006), both of which are driven by the surface electric field. Micron-scale dust is levitated to ~10 cm, while ~0.1-μm dust is lofted to altitudes >100 km. The Apollo 17 Lunar Ejecta and Meteorites (LEAM) surface experiment directly detected the transport of charged lunar dust traveling at up to 1 km/s (Berg et al., 1976). The dust impacts were observed to peak around the terminator regions, thus suggesting a relationship with horizon glow.

Methodology and Instrumentation

All the existing observations of the transport of charged dust were acquired by instruments designed to measure something else (e.g., LEAM was set up to detect hypervelocity impacts). Therefore, it is necessary to make targeted in situ measurements of dust-plasma-surface interactions on the Moon in order to fully understand this alien environment.

The necessary in situ measurements for characterizing the lunar dust-plasma environment are summarized in the table below. They can be achieved from orbit to give a global-scale view, or from the surface for a local perspective. To optimize the characterization of this environment, it is recommended that measurements from orbit and the surface be coordinated, so the connection between processes at these scales can be understood. Since not every point on the lunar surface experiences the same conditions (e.g., locations near the poles will be quite different from those nearer the equator), observation from several landers would be advantageous.

The instruments described have a high TRL, and many of them are standard on heliophysics and planetary missions. Based on anticipated measurement requirements, the mass and power needs are reasonable, and the size can be kept relatively small. Telemetry rates are relatively low, but will depend on the time resolution of measurements.

Benefits of Astronaut Involvement

Astronauts could be used to distribute a network of sensors on the lunar surface. In addition to measuring the natural environment, the instrumentation described above will also detect the charge on the astronauts and the dust transport caused by their moving around on the surface. This will reveal how astronauts and equipment are electrically coupled to the dust-plasma environment.

Fourier Transform Spectrometer (to measure exospheric dust concentrations)	3 kg	10 W	10 kbps	Mini-TES, ATMOS, CIRS
LIDAR (to measure exospheric dust concentrations)	3 kg	10 W	5 kbps	
Impact Sensor (to measure distribution of dust mass, velocity, and charge)	2 kg	2 W	1 kbps	Cassini
Optical Sensor (to measure exospheric dust size and concentration distributions)	1 kg	2 W	1 kbps	Commercial Particle Counter
Electron and Ion Spectrometers	1.5 kg	1.7 W	1 kbps	Wind
Electric Field Boom and Sensor	3 kg	1 W	1 kbps	FAST, STEREO, THEMIS, Polar, Cluster-II
Magnetometer Boom and Sensor	3 kg	1 W	1 kbps	Wind, FAST, Lunar Prospector
UV Spectrometer	8 kg	8 W	1 kbps	SoHO

Composite of five Surveyor 7 lunar mission photographs showing evidence of a suspended layer of dust (Rennilson and Criswell, 1974).
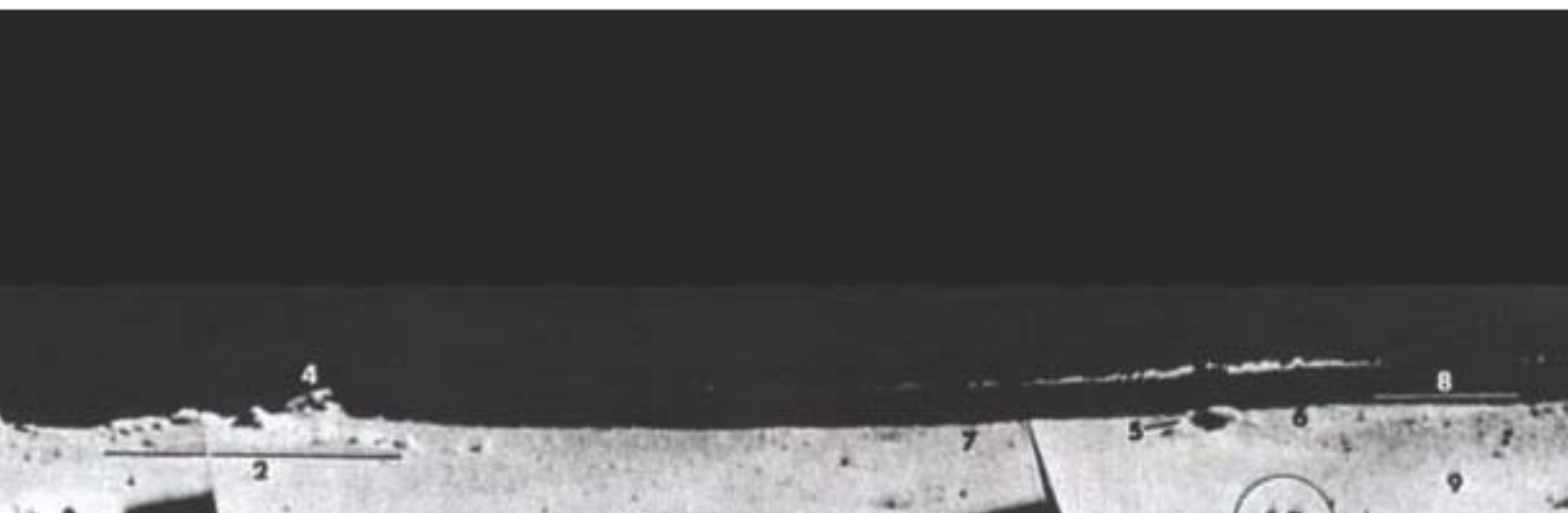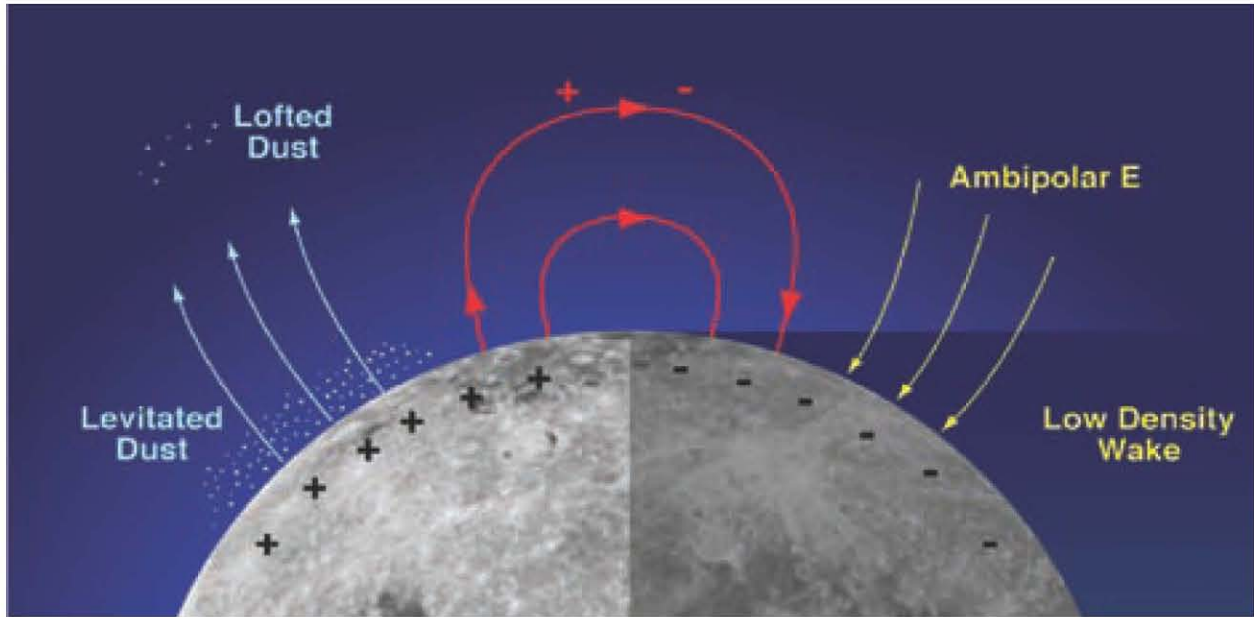
Illustration of the induced electric field resulting from charged lunar dust at the surface.

Wider Benefits

This work has significant implications for the design and implementation of experiments in other fields, such as astronomy and astrophysics, lunar geology, lunar environmental characterization, and operational environmental monitoring. It will also further our understanding of the environments of other airless bodies, such as Mercury and the asteroids (Colwell et al., 2005).

The characterization of this environment, and the resulting development of dust mitigation technology, will permit a sustainable exploration program requiring surface operations, particularly astronaut EVAs. This will pave the way for future missions, ISRU activities, and the ultimate commercialization of the Moon.

Horizon glow and other unexplained phenomena caused by the electrostatic transport of lunar dust discovered during the Apollo era hold a great fascination for the general public (Bell, 2006); therefore, this work will also be of great benefit to NASA's Education and Public Outreach program.

Measurements of the lunar natural environment from orbit and from the surface

Continue monitoring of natural environment background and impact of surface operations

Deploy large-scale surface network to monitor and make predictions

International Space Station photo showing a complex collection of exposed surfaces that must survive surface charging in space.

Charging of Structures in Space

Spacecraft acquire charge when exposed to space plasma and radiation environments due to the unequal collection of ion and electron currents. Accumulation of excess electrons can threaten spacecraft because electrostatic discharge arcs may be produced from localized, highly charged regions which degrade materials and damage or destroy sensitive electronic components. Physical processes that generate the space environments responsible for strong spacecraft charging have been well characterized by the space physics community. Geomagnetic storms are one example, producing hot electrons in the Earth's outer magnetosphere capable of charging spacecraft surfaces to voltages exceeding a few thousand volts. Energetic Van Allen radiation belt electrons generated by geomagnetic storms and the interaction of the solar wind with the Earth's magnetosphere are now known to be a significant threat to spacecraft, because they penetrate spacecraft delivering damaging radiation doses to electronic circuits and other sensitive internal spacecraft components.

Even in LEO where the plasma environments are relatively benign, the International Space Station has been shown to charge due to an interaction of its solar arrays with the ambient plasma environment. Plasma Contactor Units have been installed on the vehicle to eliminate excess charge and control the vehicle voltage to program requirements. Knowledge of the average and extreme conditions that a spacecraft will encounter in the space environment is an important consideration for designing a vehicle for reliable and safe operation in charging environments.
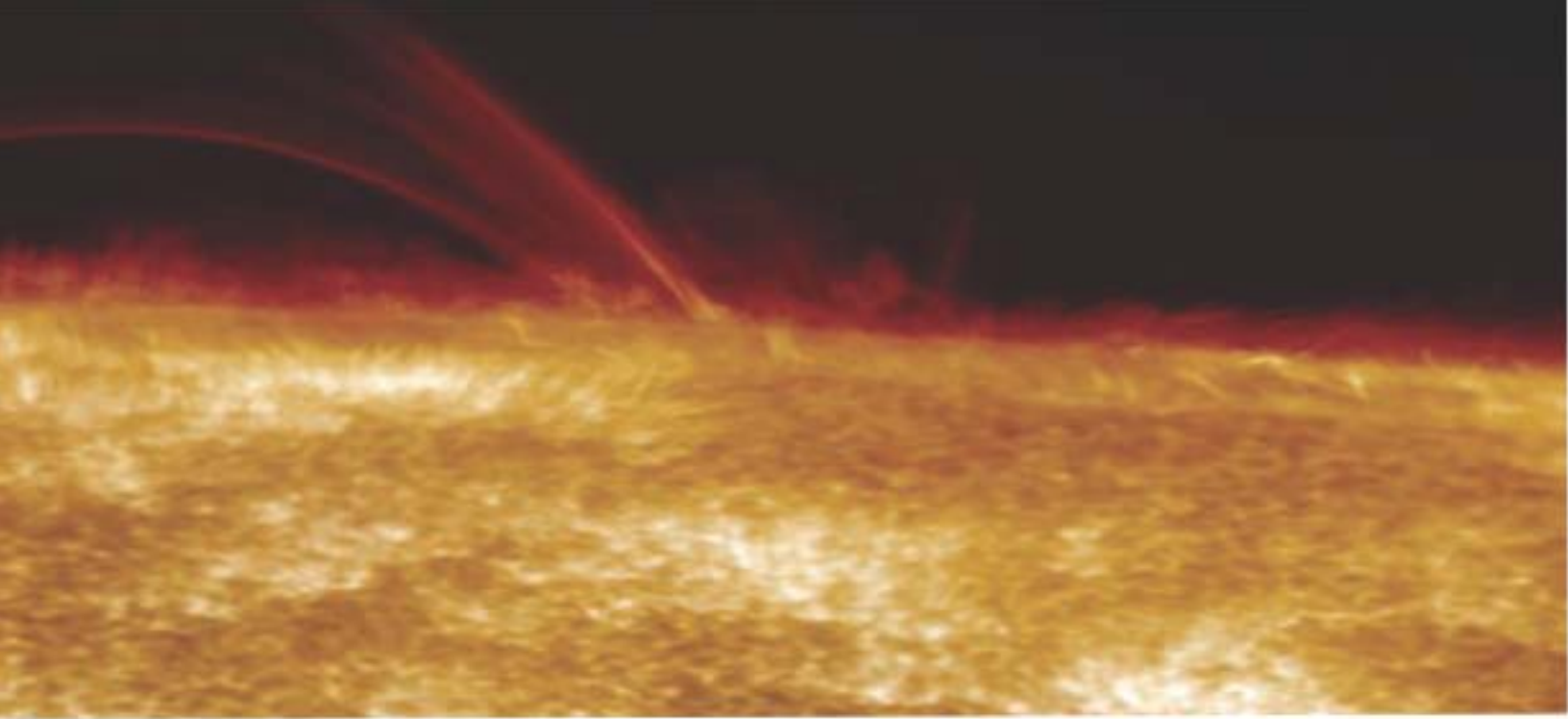
Space Weather, Safeguarding the Journey

• Understand and Predict Space Weather Impact on Robotic and Human Productivity

• Characterize Radiation Bombardment on the Lunar Surface and Subsurface

Introduction

Space radiation hazards are of serious concern to future human and robotic exploration of the Moon and Mars. Timely and reliable forecasts of the radiation environment are required in order to manage the radiation exposures of the crew, and models of the environment are needed to guide the design of reliable systems and the planning of crewed missions:

• Galactic cosmic radiation (GCR) is an ever-present background that originates from outside our solar system. It produces single event effects (SEEs) in electronics. The exposure of astronauts to GCR can produce chronic (but not acute) health effects;

• Large solar energetic particle (SEP) events are dangerous for astronauts outside the Earth's atmosphere and magnetosphere. To minimize the hazard SEPs pose, we must develop the ability to predict when and where they will occur, and we must provide adequate shielding against them. SEPs cause both SEEs and total dose effects in electronics. For critical life support systems, the latter entail additional

associated hazards for the crew. We need models that predict credible worst-case SEP events for spacecraft design and mission planning;

• There are unique and rapidly varying radiation, plasma, dust, and electrodynamic environments in the vicinity of the Earth, Moon, and planets.

The heliophysics science community is actively developing the capability to predict radiation and electrodynamic hazards in space through the study of sources of radiation and plasma variations on the Sun and in its corona. This community is learning to more completely characterize the radiation environment and its impacts on robotic and human explorers. There are also new hazards on the Moon due to complex dust-plasma interactions and the difficulty of working in a charged-dust environment. The challenges of understanding the space environment and its impacts are not restricted to the Moon. Lessons learned from the lunar environment must be applied to assess the impacts of radiation for long-duration space travel (e.g., to Mars), and to understand working conditions in other planetary environments. Understanding, characterizing, and learning to predict the impacts of radiation on the Moon, Mars, and in interplanetary space are central activities in which heliophysics plays a continuing role in extending the reach of space exploration.

Space weather research is at a critical juncture. Solar and space physics is fundamentally a research-driven scientific field. However, the grand challenge of developing timely and reliable space weather tools for missions to the Moon and beyond requires that we align our research goals with this new challenge in order to acquire the knowledge needed to create these tools. To quote the NRC Report of the October 2005 Wintergreen Conference (Baker et al., 2006, page 2):

"There was general agreement among the participants that it is in this area that the solar and space physics community can, through improved characterization and understanding of the sources of space radiation, contribute substantially to NASA's radiation management effort and to the Vision for Space Exploration."

Our most sophisticated and reliable space weather predictions will be derived, most likely, from the coordination and integration of the distributed, simultaneous measurements

of the collection of spaced-based observatories known as the Heliophysics Great Observatory. There is a critical need for a space weather monitoring system on the Moon to permit radiation exposure management by the crew both in the event that communications with Earth are lost and to gain experience with real-time in situ exposure management for future missions to Mars. Further, radiation transport models must be validated over the energy ranges where doses are most significant in order to accurately predict the radiation environment within shielded locations. A more complete understanding of the lunar plasma environment, and its impacts on the transport of dust, is also required. The scope of these issues does not fit neatly into either a purely scientific or a purely operational realm; it requires a combination of both, creating unique challenges for strategic planning and implementation.

To understand how we should address space weather research and operations, it may be useful to consider its historical context. Space weather became an increasingly significant issue through the course of the space age due to our increasing reliance on geospace satellite technologies. Disturbances and variations in the solar wind on Earth's magnetosphere continually change the geospace radiation and plasma environment. Solar storms are most often induced by coronal mass ejections (CMEs), which are released from the Sun, plow through the interplanetary medium, and form shocks and concomitant high levels of shock-accelerated particle radiation. When CMEs impact the Earth's magnetosphere, they induce a series of systemic reactions that are not fully understood but lead to modifications of the Earth's ionosphere, thermosphere, and mesosphere, enhancements and changes in the Earth's radiation belts, disruption of the large-scale magnetosphere, induction of large-scale electrical currents on Earth, and a host of other effects. These changes to the geospace environment have implications for power grids, communications, satellite drag, and global positioning systems (GPSs), among other issues. The list of geospace effects caused by space weather will continue to grow as we learn to harness the many potential assets of geospace. Reliable space weather models will provide us with the tools to design reliable spacecraft. They will provide us with a way to predict when large-scale currents will be induced in power grids, when air traffic on polar routes may experience communication disruptions, and when GPSs may fail.
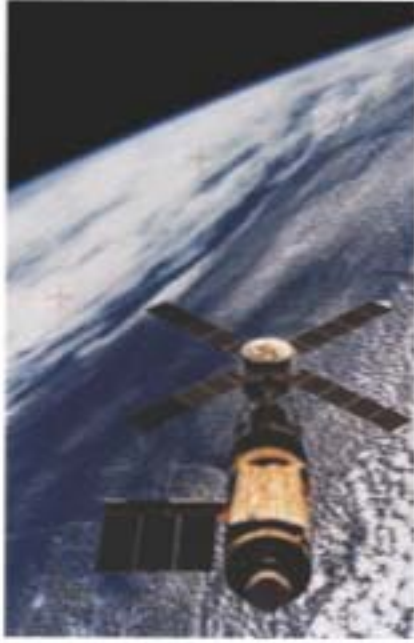
Skylab De-Orbits Because of Atmospheric Drag

Pressure of the remnant atmosphere at the altitude of the Space Station orbit is less than the best vacuum produced in chambers on Earth. The few atoms that do remain, however, are an important consideration to the ISS Program. A drag force sufficient to gradually reduce the Space Station's orbital energy is produced by collisions with the atmospheric particles at the nearly 8 km/s orbital velocity of the vehicle, which lowers its altitude over time. To compensate for the drag, ISS operators must periodically fire thrusters on the ISS Service Module or use engines on visiting Space Shuttles or Progress rockets to raise the orbital altitude.

The density of the tenuous atmosphere at ISS altitudes is controlled primarily by two factors: the extreme ultraviolet photon output of the Sun which varies over the Sun's 11-year solar cycle and heating of the atmosphere at polar latitudes during geomagnetic storms. An understanding of the solar and geomagnetic conditions as a function of phase in the solar cycle is an important factor in determining the amount of fuel that must be flown to the ISS for use in maintaining the altitude of the vehicle.

Skylab orbiting Earth.

The Vision for Space Exploration has introduced a new twist in our efforts to understand and predict space weather. It has increased concerns about the hazards in the space environment to include beyond geospace. Spacefaring is a mode of navigation, and as for all other forms of navigation, there is an intimate link between how we travel and what we must travel through to get where we are going. The design of our vessels, whether they are ships, airplanes, or spacecraft, must take into account the properties and extreme conditions of the medium through which they travel. Seafarers have historically had a deep knowledge of, and appreciation for, the weather, as do airline pilots and dispatchers.

Although the challenges in reliable space weather prediction involve scientific problems, the challenge itself is not entirely scientific. Scientific understanding of the various hazards must be used to develop mitigation and operation strategies. Spacefaring entails inherent risks that must be understood and quantified in reasonable detail.

The tasks are daunting, and they cannot be achieved by heliophysics science alone. Groups with broad expertise in space science, mission operations, radiation, biological impacts of radiation, and astronautics should address the systems and strategies for understanding and dealing with space weather. Members of the astronaut corps should continue to advance their understanding of space weather.

There is a compelling argument for creating positions for scientist-astronauts trained to understand space weather and possibly operate lunar space weather observatories.

At this stage, the heliophysics community is still advancing the capability to predict space weather. Because of the inherent complexity of the environment, the task of developing truly predictive radiation models is a worthy challenge. Although current models for space weather prediction are not up to many of the tasks needed by mission operators and planners, lessons learned from the development of global terrestrial weather models show that computational technologies are advancing at a sufficient pace that future models of increasing sophistication and predictive capability are possible. It may well be necessary to implement a strategic planning process that specifically targets space weather capabilities for the Vision for Space Exploration, which has stakeholders from both the space science and exploration communities. In a series of such planning exercises, we may identify and accurately categorize both the nowcasting and forecasting capabilities available today, a prioritization of those capabilities that will need further development, and a strawman of the space weather instrumentation needed on lunar outposts and Mars missions.

The subsections that follow this introduction outline many of the capabilities that are needed to safeguard the journey of human and robotic explorers. Section 2.1 describes methodologies and instrumentation needed to understand and predict the impact of Space Weather on robotic and human productivity. Section 2.2 describes methodologies and instrumentation to characterize radiation bombardment at several locations on the lunar surface and subsurface. These sections describe the nature of the problems that need to be addressed; they constitute neither an implementation plan nor a prioritized list. A space weather strategic planning process, involving members from both the space science and exploration communities, is needed to identify strategies and priorities, and to develop an implementation plan that ensures that the success of the Exploration program is not jeopardized by a lack of understanding of the impacts and hazards of space weather.

Image from Startracker camera showing the Moon illuminated by Earthshine (top) and obscuring the Sun to reveal the coronal and zodiacal light (and maybe some horizon glow, too) with a saturated Venus in the distance.

2.1 Understand and Predict Space Weather Impact on Robotic and Human Productivity

Summary

Space weather impacts the productivity of human and robotic explorers. Understanding and being able to predict space weather and associated impacts will mitigate operational risks at the Moon. Steps to achieve this include:

- Use the coordinated, distributed, simultaneous measurements provided by the heliospheric great observatory to drive predictive models of space radiation at the Moon;

- Use real-time measurements on the Moon to account for the effect on the local environment of the anisotropy in solar particle events and for redundant nowcasting of space weather;

- Use real-time measurements on the Moon to determine the radiation hazards, the electrodynamic plasma environment, and effects of dust dynamics and adhesion;

- Characterize the dust environment at several locations on the lunar surface to better understand the operational environment of the Moon.

Value

Mitigating the exposure risk requires the delivery of reliable operational products, based on monitoring of hazardous radiation, to mission operators, planners, and crews. It will also require a dedicated effort to generate near real-time operational data that are supported by a fundamental understanding of the underlying physics. The infrastructure to monitor space weather over timescales of days to hours to even minutes exists. This science is of high intrinsic value because developing such a predictive capability requires the solution of many as yet unsolved and longstanding problems in heliophysics.

Deployment of onsite resources that will accurately measure the local radiation environment will be invaluable in the event of geocommunication disruptions, when lunar inhabitants must rely only on local resources to manage their radiation exposure (Neal and Townsend, 2001). Onsite measurements would also provide direct input to predict the plasma and electrodynamic effects on the lunar dust environment, and provide a redundant forecasting capability and training for future Mars missions.

Description

The Moon's tenuous exosphere is immersed in the plasma and energetic particle environment of the heliosphere. The hazardous radiation from intense SEPs arises from solar events such as flares and CMEs generated through the dynamic and often explosive reorganization of intense magnetic fields at the Sun. CMEs plow through the solar wind, forming shocks, which, in turn, accelerate protons to energies typically in the range from less than 50 to 1000 million electron volts. These high-energy protons interact with the material of spacecraft, the components of the spacecraft control systems, space habitats, space suits, and human tissue. In doing so, they produce dangerous secondary particles that can cause radiation effects in spacecraft electronics and damage DNA throughout the human body. In humans, the radiation can produce acute effects such as sickness, fatigue, and damage to the skin and eyes, as well as chronic effects including cancer, damage to the central nervous system, cataracts, and heart disease (NCRP Report No. 153, 2006). To mitigate the harmful effects of radiation, the heliophysics science community is advancing its understanding of the sources of particle radiation and developing predictive models of the solar and heliospheric phenomena that generate this radiation.

Apollo 17 Astronaut Harrison Schmitt uses scoop to retrieve lunar samples during EVA.

At present, we do not fully understand the mechanisms that trigger CMEs or solar flares. We have preliminary models of energetic particle acceleration at the shocks driven by CMEs, but these models are still primitive in their predictive capabilities. Current and future Science Mission Directorate (SMD) missions will attempt to fill holes in our understanding, paving the road to predictive models of space weather. The current Solar Terrestrial Probe (STP) STEREO and Hinode (Solar-B) missions, the future Living With a Star (LWS) Solar Dynamics Observatory (SDO) and Radiation Belt Storm Probe (RBSP) missions, and the Solar Sentinels mission concept may help develop the physical understanding necessary to reliably model and predict the radiation environment at 1 astronomical unit (AU) and understand the dominant mechanisms associated with the energization of particles that produce harmful radiation. This information will then be used to specify the physics-based space environment models that will be driven by coordinated, distributed observations from a space monitoring system (Baker et al., 2006). The targeted outcome is reliable predictions of space weather in support of human and robotic mission operations in the lunar environment. This network of coordinated space weather observations and models is a first step for the more comprehensive forecasting needed to support missions to Mars.

The highly variable plasma environment at the orbit of the Moon is due both to the changing conditions of the impinging solar wind and traversals of the Earth's magnetosphere. (Stubbs et al., 2007a) The Moon can enter the hot and tenuous plasma sheet in the Earth's magnetotail, causing increased electrostatic potentials. The resulting surface charging can drive the electrostatic transport of charged lunar dust. The lunar dust-plasma is highly susceptible to space weather. Therefore, observations of the dust-plasma environment during a range of different solar and magnetospheric activity conditions are needed.

The interaction of solar wind and energetic particles with the lunar surface produces large surface electric fields (analogous to spacecraft charging). The electric fields were remotely sensed by Lunar Prospector (Halekas et al., 2005a). The lunar surface potentials are large (up to many kilovolts negative on the night-side hemisphere that is immersed in hot energetic plasma). In sunlight, where photoemission dominates, the lunar surface potentials are typically a few volts (positive). This large potential difference at the day-night terminator causes very large electric
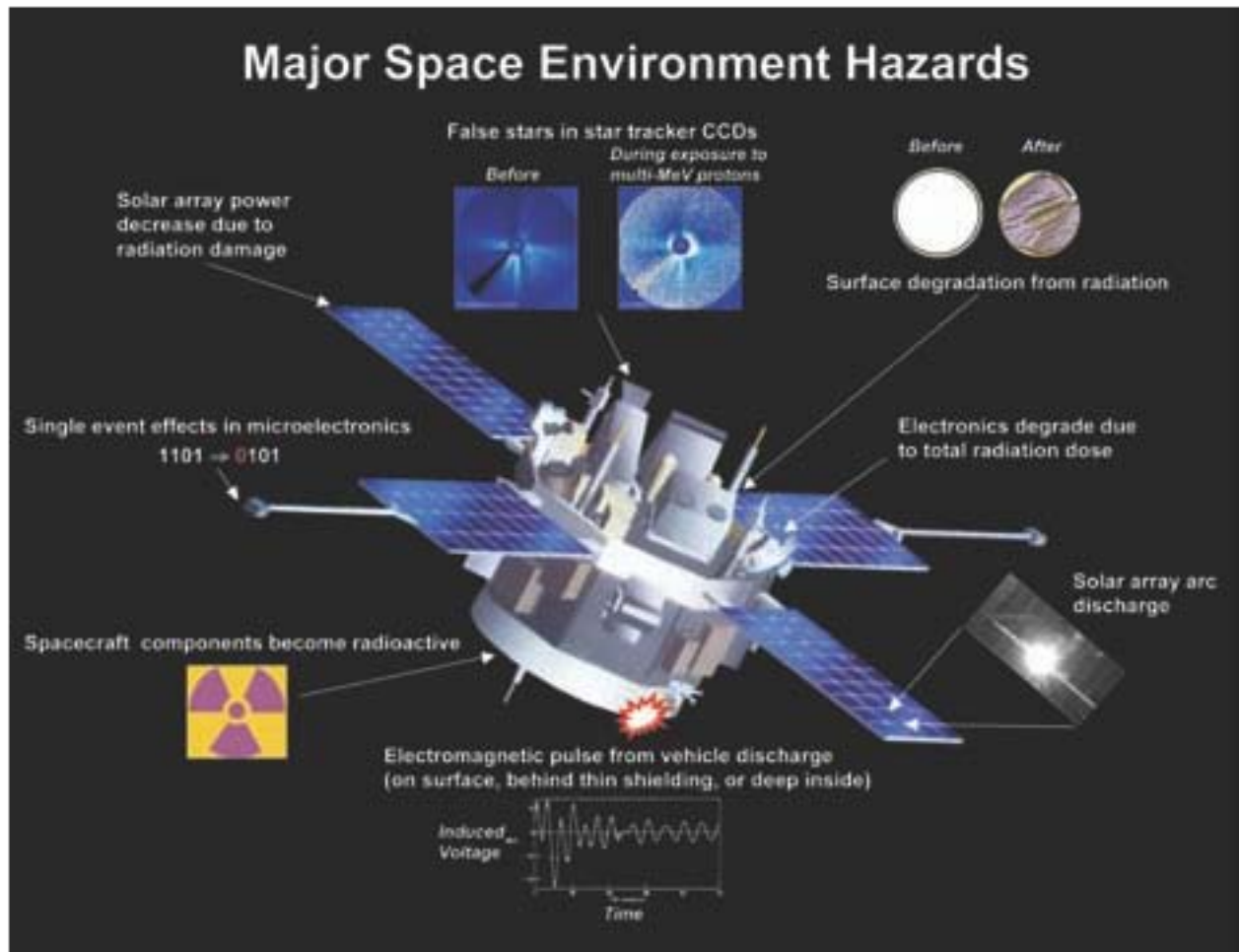
fields, with associated hazards to astronauts and equipment, and these fields affect the transport of charged dust grains on the lunar surface and in the tenuous lunar atmosphere. The charged dust grains pose significant hazards to machinery and lunar inhabitants; the nature of this dust hazard depends on the properties of both the lunar plasma environment and the dust grains. The electrostatic plasma-dust interactions are complex, often mitigated by SEP events (Halekas et al., 2007), and are neither well characterized nor well understood.

The colliding solar wind produces an ion-free cavity behind the Moon, but solar wind electrons traveling along the magnetic field (which is generally not parallel to the solar wind) can enter the cavity. Very large charge separation electric fields, critical to kinetic-plasma interactions, are produced at the solar wind terminator, and these in turn produce a variety of intense plasma waves and beams.

Methodology and Instrumentation

To significantly improve forecasting of the hazardous SEP events, the STP STEREO and Hinode, the LWS SDO and RBSP, and Sentinels missions will be needed. STEREO will provide understanding of the development of CMEs and Hinode will provide insight to the onset of explosive events on the Sun's surface. RBSP will explore acceleration processes within the Earth's magnetosphere, and the LWS Sentinels, as currently envisioned, will provide multipoint measurements in the inner heliosphere (0.25 – 0.75 AU) to directly study the SEP acceleration processes. Overlap with the LWS SDO mission, presently being developed for a 2008 launch, would provide simultaneous detailed optical/EUV/x-ray imaging and diagnostics of the Sun to determine the initiation of the CMEs/flares that produce SEPs, and their characteristics.

Comprehensive measurements of the plasma, energetic particle, and field environment close to the Moon are needed to understand the lunar dust-plasma interactions on the lunar surface and in the exosphere. Comprehensive measurements of the near-lunar surface environment have not been made and are needed. A small, low (<100 km) lunar-orbiting spacecraft with a comprehensive set of plasma, suprathermal and energetic particles, electric and magnetic fields, waves, and composition measurements together with surface measurements in many locations (see, e.g., Objective 1.5 for surface instrumentation) would allow comprehensive characterization of the Moon's complex electrodynamic dusty plasma environment.

Major Space Environment Hazards

Solar array power decrease due to radiation damage

False stars in star tracker CCDs
Before
During exposure to multi-MeV protons

Before   After

Surface degradation from radiation

Single event effects in microelectronics
1101 → 0101

Electronics degrade due to total radiation dose

Solar array arc discharge

Spacecraft components become radioactive

Electromagnetic pulse from vehicle discharge (on surface, behind thin shielding, or deep inside)

Induced Voltage

Time

Schematic illustrating various space weather impacts on robotic spacecraft systems.

For an operational and monitoring system for space weather in the lunar environment, multiple observations are needed; these include solar imaging, in situ solar wind measurements at the Sun-Earth L1 Lagrange point, and lunar orbiting and surface measurements. In preparation for future operations and monitoring of the radiation environment at Mars, a ring of small spacecraft arrayed around the Sun at 1 AU would provide needed input.

A space weather monitoring system using the Moon as a platform can provide redundant actionable information for mission management. These measurements provide direct input to predict the effects on the lunar dust-plasma environment. A suite of instruments can be designed to fit in the existing architecture. A major goal is learning how to run an operational system in the harsh lunar environment.

Lunar orbiting spacecraft should include the following instruments:

Full 3-D Plasma Ion and Electron Sensors	3 kg	3 W	2 kbps	THEMIS
Energetic Ion and Electron Sensors, Covering from Just Above Plasma Energies up to >100 MeV	3 kg	4 W	1 kbps	Wind
3-D Electric Field Instrument	10 kg	5 W	2 kbps	THEMIS
Magnetometer	1 kg	1 W	1 kbps	THEMIS
Plasma Waves Instrument	3 kg	3 W	1 kbps	FAST
Ion Composition Instrument (highly desirable)	4 kg	4 W	1 kbps	FAST

Surface instrumentation for Objective 1.4 includes the following.:

Ion and Electron Electrostatic Analyzers	3 kg	3 W	2 kbps	Wind
Ion Composition	4 kg	4 W	1 kbps	FAST
Energetic Ions and Electrons	1.5 kg	1.7 W	1 kbps	Wind
Magnetometer Boom and Sensor	3 kg	1 W	1 kbps	THEMIS
E-field Booms and Sensors	15 kg	8 W	1 kbps	THEMIS

Extent of Astronaut Involvement
For the surface instruments, humans would be highly desirable to put the instruments in appropriate locations and to move them around as needed.

Wider Benefits
This work will be useful in resource mapping.

LWS SDO, RBSP and Sentinels, to determine operational requirements; Lunar Plasma Orbiter for assessment of electrical fields and dust hazards

Lunar surface instrumentation to establish operational guidelines

2.2 Characterize Radiation Bombardment on the Lunar Surface and Subsurface

Summary

The overarching goal is to characterize the radiation bombardment on the lunar surface and subsurface in order to better understand the operational environments on the Moon, to validate and improve radiation models, and to improve our understanding of the radiation environment of Mars. We describe here scientific investigations to study, characterize, and monitor the lunar radiation environment by understanding the effects of solar activity, radiation from extra-solar sources, and induced radiation from the lunar surface on the operational environment.

Value

Results of this characterization, plus an understanding of the biological effects of this environment, will enable the creation of specifications for radiation shielding, mitigation techniques, and countermeasure strategies. Appropriate radiation mitigation techniques are essential for ensuring crew health and the prevention of instrumentation malfunctions during extended stays on the Moon. These measurements will be used to improve and validate predictive radiation transport models.

Photograph of Fred; a man-made model of a human torso flown on the ISS to measure typical radiation doses to internal human organs.

Radiation Hazards for Humans

NASA has the moral and legal obligation to protect its astronauts from the harmful radiation in space. The ionizing radiation environment in space is continuously monitored by NASA with the assistance of NOAA so that unnecessary radiation exposures of the crew can be avoided. The radiation exposures of the crew members are also monitored. This radiation monitoring is done with various instruments. Some monitor the areas where astronauts live and work. Others are worn by the crew members. The measurements from these monitors are used to determine the radiation doses to the skin, eyes, and internal organs of each astronaut.

Doses to the internal organs must be calculated. To check these calculations, NASA flew Fred (shown in the figure) on the International Space Station. Fred is a man-made model of a human torso. Fred was instrumented with radiation monitors in his internal organs. Fred also wore monitors on his clothing just as an astronaut might. The internal measurements from Fred were used to confirm the calculations used to estimate the internal radiation doses for the crew.

Description

The radiation environments at the Moon and Mars originate from GCRs and the solar particle events (SPEs). The primary effects are total radiation dose (dominated by protons) and single-event effects in electronics (due principally to ions with higher atomic numbers). The total dose and effects from individual, highly-ionizing particles are important for both the human component and the electronic systems components of long-duration lunar missions, as the crew will depend on the health of both for a successful mission.

In addition to the primary, incident radiation, one must consider the lunar albedo radiation (principally neutrons) produced by the interactions of GCRs and SEPs in the surface. The neutron albedo can contribute as much as ~18% to the effective dose received by crewmembers when the radiation environment is dominated by GCRs. When SEPs dominate, the neutrons contribute ~2% to the total dose (Adams et al., 2007b). The case for Mars is more complex because the Martian atmosphere attenuates GCRs and SEPs observed at the surface, but atmospheric nuclear interactions generate neutrons, adding to the albedo from the surface (Saganti et al., 2004). Therefore, secondary neutrons make a larger contribution to the environment at Mars. Prediction of the environment in subsurface or shielded locations on the Moon and Mars relies on radiation transport codes. These codes (Townsend, 2005; Tweed et al., 2005; Andersen et al., 2004; Townsend et al., 2005) require models of the relevant nuclear fragmentation cross-sections and knowledge of the energy spectra (composition and distribution in energy) in the radiation environment.

During the onsets of some SPEs, the highest energy (>100 MeV) particles exhibit a large anisotropy as they stream along the interplanetary magnetic field (S´aiz et al., 2005). The anisotropy, combined with the shadowing effects of the entire Moon and local topography, can lead to differences in the actual exposure to lunar-based assets when compared to interplanetary measurements. While these shadowing effects are expected, their details have not been quantified nor modeled, thus emphasizing the importance of monitoring the radiation environment at the locations of interest.

Methodology and Instrumentation

- In the case of GCRs, it is sufficient to measure the level of solar modulation because the flux is isotropic and time-invariant outside the heliosphere. Conventional ground-based (Usoskin et al., 1999) or space-based measurements are sufficient to determine the modulation (Wiedenbeck et al., 2005). The models of GCR modulation are adequate for Mars because the GCR flux is only ~2% higher than at Earth (Webber et al., 2004).

- To know the actual proton and heavy-ion environment in SPEs requires that the energy spectra and anisotropies of SEPs be measured as a function of time from 20 to >600 MeV; this energy range will account for ~80% of the effective dose behind typical shielding. It is currently impossible to predict the SPE intensity to sufficient accuracy with current models or proxies. To account for radiation effects on electronics, proton measurements must be extended down to 10 MeV. Heavy ions need to be measured over energy ranges with stopping ranges similar to those of the protons. It is important to ensure that the measurement techniques perform without significant background or dead time effects in the most intense SPEs as the need for a larger collection area for the rare, highly ionizing elements can be at odds with the need to accurately measure the most intense events.

SEP measurements; specification of worst-case environments to guide mission design trade

Neutron albedo measurements prior to crewed missions in excess of 3 months

Regolith packing density investigation for lunar/Mars habitat construction

- The neutron albedo contribution to the effective dose has been estimated using the Lunar Prospector measurements between 0.6 and 8 MeV. Neutrons in this range account for only about one-third of the effective dose from neutrons. To account for 80% of the dose, neutron measurements must be extended to ~200 MeV, and this will require new instrumentation. The Low Energetic Neutral Atom (LENA) instrument on LRO will extend neutron measurements only to ~15 MeV.

- Radiation transport codes for protons can be tested and modified using ground-based accelerators. Because of the broad ranges of energies and ions in GCRs, it is more economical to test codes in the natural environment. This can be done on polar balloon flights (Adams et al., 2007a) or in space (Kasper et al., 2007). While lunar regolith simulant is adequate for these tests, the uncertainty in doses below the surface or under locally constructed regolith shields depends on the shielding thickness, which requires knowledge of its density and porosity. While the subsurface porosity in known down to a few meters, the porosity of excavated regolith must be measured on the Moon.

- The measurements to determine GCR spectra can be obtained from neutron monitors on Earth or charged particle telescopes in space. The SEP measurements, however, must be made outside the magnetosphere in the Earth-Moon neighborhood. For SPE anisotropy studies, a spinning platform minimizes the number of detector assemblies required to measure the particle pitch angle distribution. Careful instrument design will ensure accurate measurements in the most intense SPEs.

- The porosity of excavated regolith can be inferred by conventional radiation measurements made on the Moon beneath excavated regolith shielding using transport codes.

An instrument package on the lunar surface would consist of the following:

Instrument Package	Mass	Power	Telemetry Rate	Heritage
Dosimeter	<0.2 kg	<1 W	0.01 kbps	Shuttle/ISS
Tissue Equivalent Proportional Counter	2 kg	5 W	0.01 kbps	Shuttle/ISS
Proton Charged Particle Telescope	10 kg	15 W	0.1 kbps	SAMPEX
Neutron Detector	8 kg	10 W	0.1 kbps	Lunar Prospector

Extent of Astronaut Involvement

The investigation of the packing density of lunar regolith can make use of human participation. The actual excavations can be made either by remote operation of an unmanned lander or by astronauts on the lunar surface.

Wider Benefits

The implementations described above address the radiation environment outside a solid body (space vehicle, Moon, or planet) and address the interactions of that environment with nearby material. The specifications of the outside environment, coupled with better models of the interactions with matter derived from both ground-based testing and measurements at the locations of interest, are necessary for applying our knowledge to future landing sites such as Mars and longer duration missions anywhere in the heliosphere.

The Moon as a Historical Record

- History of the Sun and Cosmic Radiation
- Understand the History of the Local Interstellar Medium from the Beginnings of the Solar System to the Present
- History of the Inner Solar System According to the Lunar Cold Traps

Introduction

The Moon has no atmosphere and acts as a collector. It collects the solar wind, cosmic radiation, and dust from the interstellar medium, and it records the Sun's irradiance environment. The Moon collects this matter both in the regolith and in cold traps, permanently shaded from the direct sunlight.

The Moon's historical record holds fundamental clues to Earth's geological history. On Earth, similar historical information has been resolved by studying deep ice cores. Earth's active geologic processes and continually changing climate make it impossible, however, to study an uninterrupted historical record over its entire history. The Moon has collected material over its entire 4-billion-year existence, and holds extremely valuable information about the history of our Sun, solar system, local interstellar medium, galaxy, and universe.

3.1 History of the Sun and Cosmic Radiation

Summary

Billions of years of the history of the heliosphere have been recorded and are preserved in layers of the lunar regolith. Every exposed surface accumulates implanted solar wind ions, solar energetic particles, and cosmic rays. Further, the surfaces are modified by particles. The result is a record in time of energy, composition, and ionization state. Some of this record consists of buried regolith that has been covered over, causing it to become a closed system that preserves a snapshot of the heliospheric environment at a specific, datable time. A series of such time capsules back 4 billion years or more would be a record of the evolution of the solar system. The Moon is the nearest and most accessible source of this information in the solar system.

Value

A history of solar-wind and energetic-particle variations over time is a data set that solar and stellar models must reproduce. These data influence concepts for the evolution of planets and their habitability. Cosmic-ray fluxes at Earth may impact cloud cover and average temperatures, and radiation levels in the past may have affected the evolution of life. A history of cosmic ray variation over time also provides data that restrict models of the evolution of the Milky Way and the universe. Understanding the time history of the solar-wind, energetic-particle, and cosmic-ray fluxes would thus have significant impact on understanding the history of our planet and the evolution of the Milky Way and the universe.

Description

The lunar surface is directly exposed to solar wind, SEPs, and GCRs. Each radiation has its own typical penetration depth, the solar wind <0.2 μm, SEPs up to a few g cm^{-2}, and GCRs approximately 150 g cm^{-2} (the attenuation depth for protons).

The surface of the Moon is covered by a several-meters-thick regolith, consisting of crater ejecta, reworked lunar rocks and rock fragments, glassy particles, and individual mineral crystals. The fine constituents (grain sizes <1 mm) are commonly called lunar soils or fines. Impactors (comets, asteroids, meteorites) are responsible for gardening, the reworking process, and for the turnover of the regolith to varying depths. From the more than one hundred samples of lunar fines returned from the Apollo landing sites that were studied, we found that only one or two samples have not been exposed to the solar wind on the lunar surface. These statistics, as well as typical surface residence times (exposure ages) of several hundred million years, illustrate that turnover and reworking processes during the last more than 3 billion years are well documented. However, documented records in the regolith on the history of the space environment, as well as on recorded solar history, are missing and require a well-planned mission of sample collection, documentation, and analysis (Sonett et al., 1991; Porcelli et al., 2002).

Solar Wind Evolution

Exposure of lunar material to the solar wind can be recognized either by the presence of trapped solar wind particles or by the solid state effects induced by the solar wind bombardment. Trapped solar wind H, He, C, Ni, Ne, A, Kr, and Xe have been detected, but not all have been completely analyzed.

Prolonged exposure of grains to the solar wind leads to the formation of a thin, amorphous layer on the surface of the grains. This amorphous coating can be recognized and studied using high-voltage electron microscopy. Other solid state effects due to solar wind bombardment (e.g., pits) have so far not been unambiguously detected. To disentangle different effects and determine ion implantation efficiency, laboratory simulations can be used.

Type	Solar Wind	Solar Cosmic Rays	Galactic Cosmic Rays
Nuclei Energies	~0.3–3 keV/u	~1 to >100 MeV/u	~0.1 to >10 GeV/u
Electron Energies	~1–100 eV	<0.1 to 1 MeV	~0.1 to >10 GeV/u
Fluxes (protons/cm²s)	~3x10⁸	~0–10⁶	2–4
Lunar Penetration Depths Protons and Alphas Heavier Nuclei	 <micrometers <micrometers	 centimeters millimeters	 meters centimeters

Penetration depths of the three major classes of particles embedded in lunar soils, depending on energy
(Lunar Source Book, Lunar & Planetary Institute)

Galactic Cosmic-Ray Evolution

GCRs dominate the average intensity of energetic particles above ~200 MeV and are affected by supernova shock waves. They are modulated by the Sun and have their lowest intensity during high solar activity. The cosmic-ray intensity has been studied using satellites for short-term variations and terrestrial and extraterrestrial materials for the longer term variations. Studies of meteorites indicate that the average galactic flux in the inner solar system has been constant only for the past few million years.

Iron meteorites have been used as GCR monitors for the last 1-billion-year (1 Ga) time period. The nuclide pair 41K and 40K (half-life 1.26 Ga) shows that the flux was smaller in the distant past. The pairs 81Kr-83Kr, 53Mn-53Cr, and 129I-129Xe are currently studied by the Solar Neighborhood Consortium for possible resolution of flux changes during the past 50 million years (50 Ma) Significant improvements in the resolution of flux changes and for the study of the evolution of the solar environment, as a result of the galactic rotation, can be expected from the application of these techniques to suitable lunar GCR monitors.

Sampling of material from identifiable layers in the lunar regolith will identify and extract datable samples. Layers sandwiched between lava flows or between layers of melted ejecta can be age-dated: an overlying igneous layer determines the minimum time since exposure and an underlying layer determines the maximum time since exposure. The sampling is carried out using standard geology techniques and is essentially identical to other lunar geology sampling. The samples must be kept uncontaminated. They do not need to be "oriented," but their context must be carefully recorded.

Methodology and Instrumentation

Two methods for enhancing extraction of samples are coring and trenching. These methods also apply to Objectives 3.2 and 3.3.

Coring: The Apollo missions produced lunar core samples up to 3 m deep. Tools required are rock hammers, pry bars, and coring drills. The coring drills require a power supply. Improved coring tools over those used during Apollo 30 years ago would be required to increase the depth range of the samples. Climbing equipment would be required to recover samples from crater walls. Excavating equipment would be required to expose deep strata.

Trenching: An alternative to coring is to dig trenches and select samples from within well-documented regolith stratigraphy. Access to trench walls allows the regolith to be

Artist's conception of trenching.

examined in two dimensions along the length and depth of the trench. Soil mechanics suggest that the sidewall of a trench will remain standing and intact at least up to 3 m in depth, and deeper trenches may be possible. Trench lengths of at least 5–10 m are required, and trench lengths of ~100 m would be ideal. The trench should be as deep as is practical. Analysis and sampling of the trench wall should occur soon after the trenching operation.

A trench can reveal fragments of continuous layers, unconformities, and marker beds, even if not all were present at any one point. In contrast, a single random core may completely miss some layers or may misleadingly show layers which are only of local extent, but that look major in the core section. Trenching is therefore generally preferred.

Coring and trenching equipment items required for this activity are identical to those used for any lunar geological prospecting and surveying, and so are likely to be used for other purposes upon human return to the Moon. The documentation of trench walls can be automated with a device that could use, for example, spectral data, x-ray fluorescence

from either x-ray sources or electron beams, and other techniques to allow chemical analysis on a pixel-by-pixel basis, much like a scaled-up automated electron microprobe.

Extent of Astronaut Involvement

Sample collection can start during robotic missions, similar to the activities carried out long ago by the Russian luna missions. However, effective sample collection activities are inherently human. They require observation and interpretation in order to collect samples at what are anticipated to be useful locations. This will be a standard activity on the return of humans to the Moon, associated with all studies of lunar history, geology, and environment. The work would begin on the first return of humans to the Moon and continue over the entire time of human exploration.

Wider Benefits

The uncovering of billions of years of the history of the heliosphere would have immense impact for many other areas of science, such as astronomy, astrophysics, and geology. It would also have very significant outreach value.

First exploratory activity

New data obtained as state-of-art instruments evolve; important results can be replicated

Spacelab manned module in the Shuttle bay.

Using Exploration Vehicle as a Science Platform

The Spacelab and Atlas missions were a Shuttle-based series, the purpose of which was to demonstrate that the Shuttle could be used as a platform for scientific studies of the Earth's local environment and to perform studies of the Earth's atmosphere and the Sun's influence over it. Biological, material science, astronomy, space plasma physics, solar, and atmospheric studies were performed. Many of the instruments in the last four disciplines flew on several flights. Active and passive experiments in space plasma physics showed the behavior of charge particles in the Earth's magnetic field as seen from the Shuttle platform. Properties of minor species in the Earth's atmosphere such as the OH radical, important in mesospheric chemistry, affecting the ozone and carbon monoxide concentration, as well as properties of some of the major species (N_2^+ first negative system in the dayglow of Earth) were measured. The solar constant and spectral content, both important for understanding the solar influence on the near-Earth environment, were precisely measured on at least four flights in order to obtain a measure of the solar input at the time of the flight and also to obtain a record of the change in the solar output over time.

These missions, all multinational in terms of crew, equipment, and science makeup, were highly successful for the heliospheric community and for the high-altitude atmospheric community.

3.2 Understand the History of the Local Interstellar Medium from the Beginning of the Solar System to the Present

Summary

As the solar system moves around the Milky Way, it encounters clouds of dust in galactic arms every few hundred million years. This dust, if dense enough, will reach the inner solar system and some will be deposited on the Moon. Lunar strata would be examined for traces of such dust. Additional anomalous dust layers will be deposited at about the same time intervals as a result of large terrestrial impacts. The two sources can be separated by compositional signatures.

Value

The layers of galactic dust would give a datum for how the solar system moves around the galaxy.

Methodology and Instrumentation

Simple geological tools will be used to collect samples of lunar soils and rocks. The samples will be selected with two specific objectives:

Image of M31, the Andromeda galaxy, shows spiraling dust arms analogous to those in the Milky Way. The solar system is expected to pass through a dust arm in the Milky Way every few hundred million years.

• Obtain samples that were exposed in the past and then protected, by lava flows, for example, from subsequent exposure. Lava flows can be age dated. An overlying igneous layer determines the minimum time since exposure and an underlying layer determines the maximum time since exposure (see objective 3.1);

• Obtain samples over the largest possible range in depths. Coring and/or trenching would be used. Samples like those described in section 3.1 would most likely be found in crater walls or excavations. Climbing equipment would be required to recover samples from crater walls.

To implement the first of these objectives, samples of the overlying and underlying igneous layers will be needed, in addition to the sample itself.

Two methods for enhancing extraction of samples are coring and trenching. These methods also apply to Objectives 3.1 and 3.3.
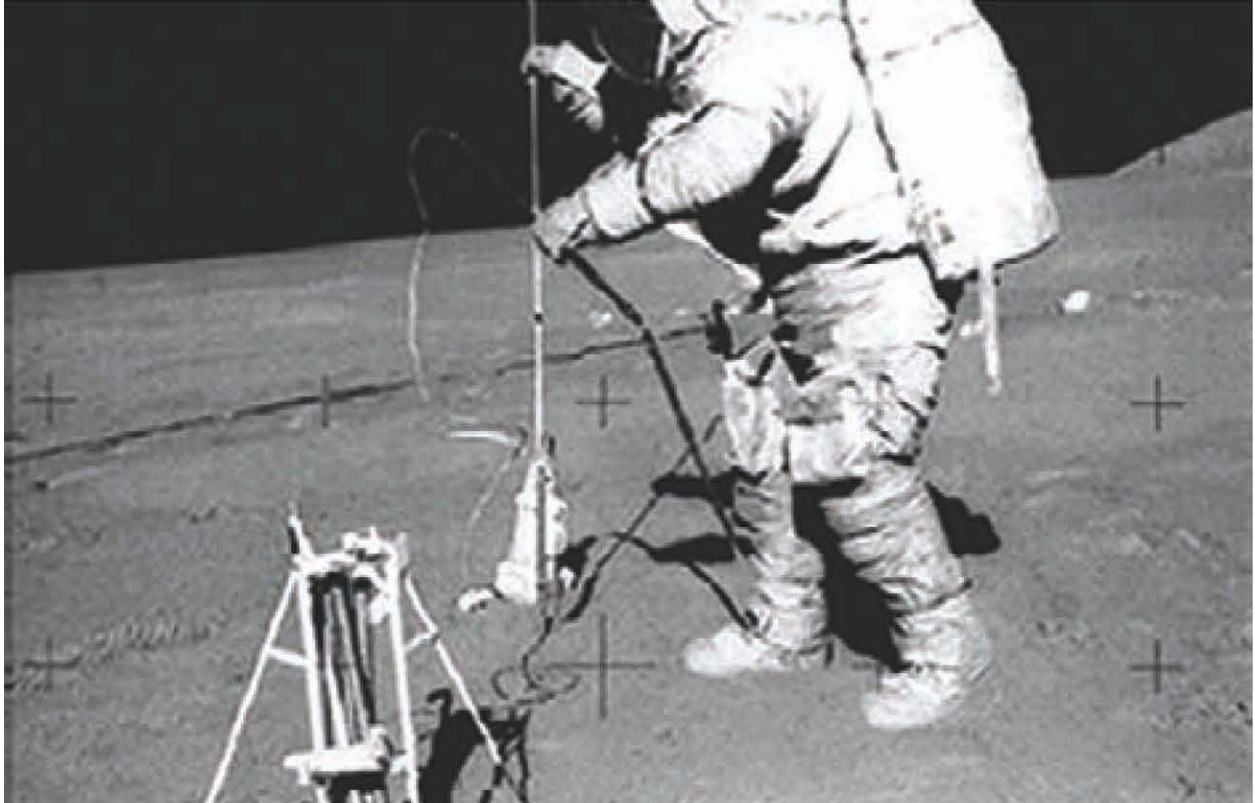
Coring: The Apollo missions produced lunar core samples up to 3 m deep. Tools required are rock hammers, pry bars, and coring drills. The coring drills require a power supply. Coring tools improved over those used during Apollo 30 years ago would be required to increase the depth range of the samples. Climbing equipment would be required to recover samples from crater walls. Excavating equipment would be required to expose deep strata.

Trenching: An alternative to coring is to dig trenches and select samples from within well-documented regolith stratigraphy. Access to trench walls allows the regolith to be examined in two dimensions along the length and depth of the trench. Soil mechanics suggest that the sidewall of a trench will remain standing and intact at least up to 3 m in depth, and deeper trenches may be possible. Trench lengths of at least 5–10 m are required, and trench lengths of ~100 m would be ideal. The trench should be as deep as is practical. Analysis and sampling of the trench wall should occur soon after the trenching operation.

A trench can reveal fragments of continuous layers, unconformities, and marker beds even if not all were present at any one point. In contrast, a single random core may completely miss some layers or may misleadingly show layers which are only of local extent, but that look major in the core section. Trenching is therefore generally preferred.

Apollo Astronaut working on the Moon's surface to collect samples.

Coring and trenching equipment items required for this activity are identical to those used for any lunar geological prospecting and surveying, and so are likely to be used for other purposes upon human return to the Moon. The documentation of trench walls can be automated with a device that could use, for example, spectral data, x-ray fluorescence from either x-ray sources or electron beams, and other techniques to allow chemical analysis on a pixel-by-pixel basis, much like a scaled-up automated electron microprobe.

Extent of Astronaut Involvement
Sample collection can start during robotic missions, similar to the activities carried out long ago by the Russian luna missions. However, effective sample collection activities are inherently human. They require observation and interpretation in order to collect samples at what are anticipated to be useful locations. This will be a standard activity on return of humans to the Moon, associated with all studies of lunar history, geology, and environment.

Wider Benefits
The uncovering of billions of years of the history of the heliosphere would have immense impact for many other areas of science, such as astronomy, astrophysics, and geology. It would also have very significant outreach value.

First exploratory activity

New data obtained as state-of-art instruments evolve; important results can be replicated

3.3 History of the Inner Solar System According to the Lunar Cold Traps

Summary
Studying the condensed material in the permanently shadowed areas near the lunar poles will help us understand the history and evolution of the inner solar system.

Value
Understanding the source of the volatiles in the cold traps will help us understand the lunar material inventory, which is important for both ISRU applications and determining the history of the solar system in the vicinity of the Earth. Understanding the migration process of particles in the lunar exosphere is important for upcoming operations on the Moon, since proposed activities will drastically increase the mass of the lunar atmosphere.

Description
The contents of the cold traps are another record of the history of the solar system in the neighborhood of Earth. There are regions near the poles of the Moon that are permanently shaded from the Sun's light and are extremely cold (T <100 K). If any water ice exists on the Moon, this is the only place where it would be stable over geologic time scales. Lunar Prospector has observed a neutron signature associated with the regions in permanent shadow that is best explained by an enhancement in the hydrogen concentration, which could be in the form of water ice. The actual contents, their distribution with depth, their source, and their accessibility are all unknown.
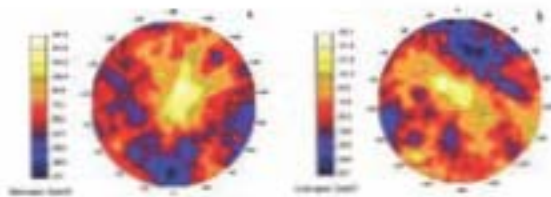
Overlay of epithermal counting rates in each 2° by 2° equal area pixel poleward of ±70° with surface relief maps of the lunar poles.

Comparison of the upper limit ratio of fast to epithermal depressions in counting rates at both poles (see figure above) with simulations shows that lunar poles' epithermal and fast-neutron data are consistent with models of buried water ice deposits. The upper limit estimate is that the measured epithermal- and fast-neutron fluxes are consistent with theoretical expectations for 40 wt.% water ice deposits buried beneath a dry regolith having a thickness of ~10 cm. However, there is a wide range of values

consistent with the data. The water ice content may be as low as 0.18% (Lawrence et al., 2006). The deposits would have total effective surface areas of ~1850 km2 at both poles (Lawrence et al., 1998).

There are two potential sources of water on the Moon: (1) episodic cometary impacts and (2) steady production from chemical interactions between solar wind protons and oxygen in the lunar regolith. Water from these sources can migrate through the lunar exosphere to the cold traps. After a cometary impact, there would be a relatively pure water ice deposit in the cold traps, which would reveal information about the composition of the comet. The varying contents and total number of ice layers are indicative of the size distribution and impact frequency of comets on the Moon. Since the Moon has neither a significant atmosphere nor a global magnetic field, the solar wind impinges directly on the lunar surface. Most of the incident hydrogen is lost from the Moon in steady state; however, the interaction can produce water by two mechanisms. First, micrometeoroid impacts melt local material, which permits the release of the implanted protons and oxygen from the regolith as H_2O. Second, the bombardment of oxides in the lunar regolith by kiloelectronvolt solar wind protons can produce H_2O by chemical sputtering. This water vapor can "hop" on ballistic trajectories around the Moon before being lost by photodissociation or photoionization. A small fraction of the water (~4%) is able to reach the cold trap of the permanently shadowed regions before being lost from the Moon. This water can accumulate and become mixed in with the regolith over geologic time scales. By sampling within the regions of permanent shadow, one can study the inventory of volatiles on the Moon over the interval that the regions have been shaded, 2–3 Gy.

Methodology and Instrumentation
Two methods for enhancing extraction of samples are coring and trenching. These methods also apply to Objectives 3.1 and 3.2.

Coring: The Apollo missions produced lunar core samples up to 3 m deep. Tools required are rock hammers, pry bars, and coring drills. The coring drills require a power supply. Improved coring tools over those used during Apollo 30 years ago would be required to increase the depth range of the samples. Climbing equipment would be required to recover samples from crater walls. Excavating equipment would be required to expose deep strata.

Trenching: An alternative to coring is to dig trenches and select samples from within well-documented regolith stratigraphy. Access to trench walls allows the regolith to be examined in two dimensions along the length and depth of the trench. Soil mechanics suggests that the sidewall of a trench will remain standing and intact at least up to 3 m in depth, and deeper trenches may be possible. Trench lengths of at least 5–10 m are required, and trench lengths of ~100 m would be ideal. The trench should be as deep as is practical. Analysis and sampling of the trench wall should occur soon after the trenching operation.

A trench can reveal fragments of continuous layers, unconformities, and marker beds, even if not all were present at any one point. In contrast, a single random core may completely miss some layers or may misleadingly show layers that are only of local extent, but which look major in the core section. Trenching is therefore generally preferred.

Coring and trenching equipment items required for this activity are identical to those used for any lunar geological prospe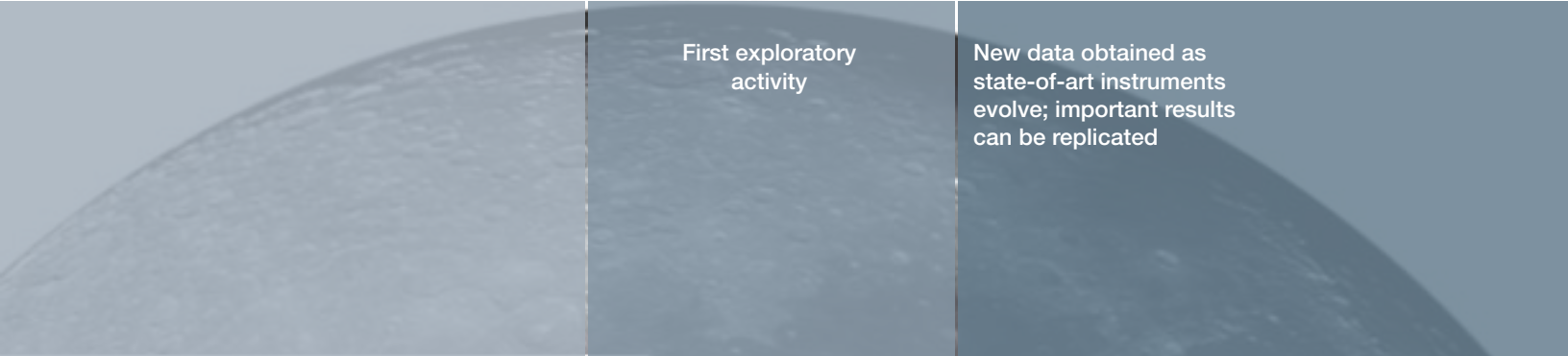cting and surveying, and so are likely to be used for other purposes upon human return to the Moon. The documentation of trench walls can be automated with a device that could use, for example, spectral data, x-ray fluorescence from either x-ray sources or electron beams, and other techniques to allow chemical analysis on a pixel-by-pixel basis, much like a scaled-up automated electron microprobe.

Extent of Astronaut Involvement
Sample collection can start during robotic missions, similar to the activities carried out long ago by the Russian luna missions. However, effective sample collection activities are inherently human. They require observation and interpretation in order to collect samples at what are anticipated to be useful locations. This will be a standard activity on the return of humans to the Moon, associated with all studies of lunar history, geology, and environment.

Wider Benefits
The discovery of water ice on the Moon would not only be a valuable resource, but would also provide valuable insight into its possible presence elsewhere in the cosmos.

First exploratory
activity

New data obtained as
state-of-art instruments
evolve; important results
can be replicated

The Moon as a Heliophysics Science Platform

- • Imaging the Heliospheric Boundary
- • Low-Frequency Radio Astronomy Observations of the Sun, Planets, and Astrophysical Objects
- • Imaging Geospace from the Moon
- • Analyze the Composition of the Solar Wind
- • The Moon as a Base for a High-Energy Optical Solar Observatory
- • The Sun's Role in Climate Change

Introduction

With its lack of an absorbing atmosphere, the Moon provides a natural observation platform from which to observe the sky, the Sun, geospace, and the Earth. Furthermore, the Moon is locked into synchronous rotation with respect to the Earth and therefore always displays the same side to Earth. A representative list of instruments that can use the Moon as an observing platform includes: instruments to observe our heliospheric boundaries surrounding and protecting our solar system; a low-frequency radio astronomy array for observing the Sun, planets, and astrophysical objects; ultraviolet and extreme ultraviolet imaging instruments to observe the global coupling from the Earth's ionosphere to its magnetosphere; instruments to observe how the Sun influences Earth's climate; and a base for a solar observatory. The Moon has many uses as a platform that would greatly benefit both heliophysics and astronomy.

4.1 Imaging the Heliospheric Boundary

Summary

The heliospheric boundaries can be imaged in extreme ultraviolet (EUV) and energetic neutral atoms (ENAs) from either the lunar surface or from a satellite in lunar orbit.

Value

Due to the sheer size of our heliosphere and the difficulty in observing its boundaries, very little is known about how it interacts with the local interstellar medium. Basic knowledge about the heliospheric boundaries is required to compare our heliosphere with astrospheres of other stellar systems. Such comparisons provide critical information on the current evolutionary stage of stellar winds and stellar mass loss rates, give insight into the stars' local interstellar environments, and possibly enable the assessment of the habitability of other solar systems.

Description

The heliosphere is the three-dimensional magnetic cavity that the magnetized solar wind forms when it expands out into the denser interstellar plasma. At the heliosphere's inner interface, the solar wind plasma slows down abruptly at the termination shock, through which Voyager-1 passed recently at ~94 AU distance from the Sun (Decker et al., 2005). Beyond this region, the solar wind heats up and becomes relatively dense and turbulent in a region called the inner heliosheath (the thickness is most likely 10–100 AU). The final boundary, called the heliopause, separates the outermost extension of the solar wind from the region of space that is completely dominated by the interstellar plasma.

Methodology and Instrumentation

Voyager-1 is the first spacecraft to cross the boundary of our heliosphere, and Voyager-2 is soon to follow. Because of the sheer size of the heliosphere, remote sensing is the only viable strategy for globally imaging these enormous structures that shelter our solar system from the local interstellar medium. To date, there are two promising techniques for imaging the heliospheric boundary: EUV and ENAs.

Hydrogen ENAs are produced in the heliosheath through charge-exchange between the shocked solar wind protons and the cold, neutral interstellar hydrogen gas. The shocked protons in this region are mostly isotropic, and some fraction of the resulting ENAs will propagate radially inward, where they can be detected by space-based platforms. The most promising energy range for studying the interactions in the heliosheath is from approximately 0.1 to 6 keV. Although

the anticipated ENA intensity from the heliosheath is low, ENA cameras on the Interstellar Boundary Explorer (IBEX) mission have already been designed to meet the requirements of imaging these ENAs with a 6-month exposure time per all-sky image. IBEX is the first dedicated mission that will utilize ENA imaging to remotely probe the heliosheath structure and, thereby, infer fundamental properties of the complex interstellar interaction.

He^+ ions from the interstellar plasma emit light at 30.4-nm wavelength through excitation by the corresponding solar line, and subsequent reemission. A large increase in number density is anticipated at the heliopause because the interstellar plasma cannot flow across this boundary. Interstellar He^+ ions beyond the heliopause would be a sizeable and measurable source of this glow, which provides a way to globally map the heliopause. It has been shown that appropriately designed instruments would be capable of measuring the milli-Rayleigh range intensity of the He^+ line with the high spectral resolution required to subtract other EUV contributions. In addition to the He^+ emissions from the interstellar plasma, there are also observable sources from the solar wind within ~20 AU from the Sun and the

Comparisons of astrospheres to our heliosphere provide critical information on the current evolutionary stage of stellar winds, stellar mass loss rates, and the stars' local interstellar environments. This information could help assess the habitability of extraterrestrial solar systems.

ENA	50–100 kg (lunar based) 10–20 kg (satellite based)	20 W (lunar based) 5 W (satellite based)	20 kbps	0.1–10 keV	5x5 deg (all-sky image)	E/E~25%	IBEX
EUV	~50 kg (lunar based) 10 kg (satellite based)	~10 W	20 kbps	4-nm band- width centered at 30.4 nm	5x5 deg (all-sky image)	0.005 nm	CHIPS

galactic emissions. These can be distinguished from the desired He$^+$ glow by their different spectral and spatial signatures (Gruntman et al., 2005). Due to the enormous size of the heliospheric boundary, variations in its intensity and morphology are anticipated, likely on the order of years.

Implementation

With its lack of an obstructing atmosphere, the Moon presents a natural and stable observation platform from which to observe the sky. Intensities of EUV and ENA emissions from the heliospheric boundaries are low. Long integration times and large geometrical factors are therefore strong design drivers. The variations of the heliospheric boundary are on the time scales of years and therefore long-duration observations are also required. The Moon and the anticipated lunar architecture infrastructure provide a platform that meets the instrument requirements (in particular, mass), and, perhaps more important, meets the requirement for long-duration observations. Observatories near the equator on the far side of the Moon would require data downlink through a relay satellite, but would be protected from unwanted terrestrial EUV and ENA emissions. A desired location for lunar deep-sky observations is in one of the deep craters at one of the poles. This location provides an acceptably quiet measurement environment while maintaining a continuous downlink directly to Earth.
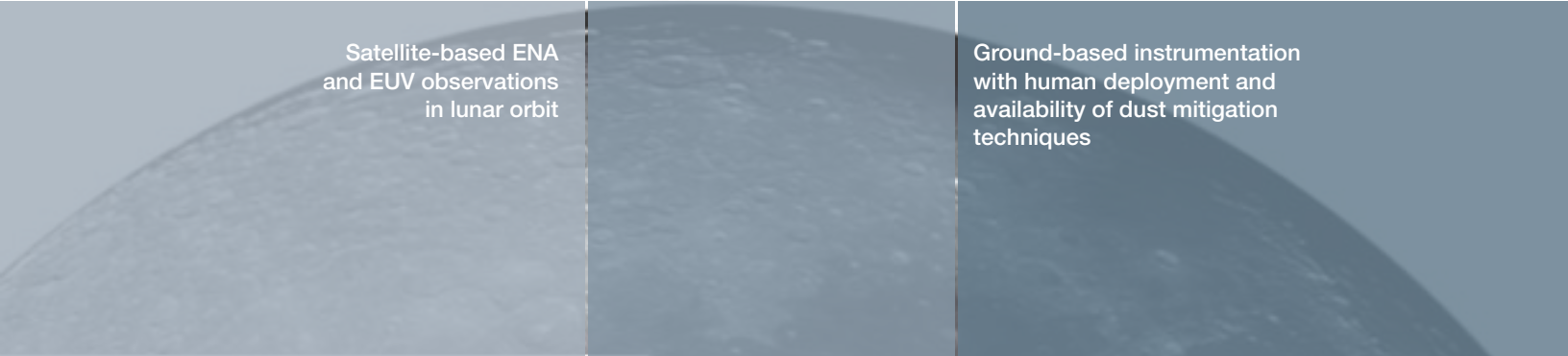
As with all lunar-based observations, the mitigation of lunar dust deposits directly onto the instrumentation is of high priority. Since dust also scatters EUV and ENAs, the spatial distribution and temporal evolution of suspended or lofted dust layers must be well characterized in order to assess the feasibility of a lunar-based observatory. Satellite-based instrumentation in lunar orbit would benefit from avoidance of the dust-related problems and from a much shorter development time, since designs could be based on existing flight hardware. On the other hand, mass constraints would be greater, which would affect geometrical factors and thus sensitivity.

Extent of Astronaut Involvement

The deployment and installation of instrumentation on the lunar surface would most likely depend on some level of human assistance. A significant development would be required to achieve a dust-controlled environment. ENA and EUV observatories would likely be co-located with other remote observation instruments.

Wider Benefits

The structure of the heliospheric boundary, and its implications for other astrospheres, is relevant to astrophysical studies of other stars and beneficial for future missions to the heliospheric boundary.

Satellite-based ENA
and EUV observations
in lunar orbit

Ground-based instrumentation
with human deployment and
availability of dust mitigation
techniques

4.2 Low-Frequency Radio Astronomy Observations of the Sun, Planets, and Astrophysical Objects

Summary
Radio emissions from solar CMEs and solar flares below 10 MHz can be imaged from the lunar surface in order to probe space from a few solar radii out to 1 AU.

Value
Observations of radio emissions from the Sun allow improved space weather forecasting, improve our understanding of shock formation and evolution in the solar wind, and enable detailed time-dependent mapping of the interplanetary electron density and magnetic field topology.

Description
Radio observations of solar activity and solar eruptions have played an important role in understanding the Sun and the Sun-Earth connection. However, the terrestrial ionosphere blocks all radio frequencies below 10–20 MHz. Frequencies below this ionospheric cutoff correspond to all radio emissions originating above 1 to 2 solar radii from the Sun's surface. Natural radio emissions occurring in this enormous volume have been observed only by spacecraft flying outside of the ionosphere. However, single spacecraft are NOT capable of imaging the radio sources. Just like an AM radio, they can detect signals at many frequencies, they can determine their strength, and they can provide some indication of where the radio signal is coming from, but low-frequency radio observations made from a single point cannot be turned into images of the source. Consequently, an image of a solar radio burst at low frequencies has never been made. Even though radio emissions from a CME-driven shock can be tracked without imaging the radio source below the cutoff, there is no way to use the details of the radio emission structure to improve understanding of space weather events or to improve prediction of their potential encounter with Earth or Mars or any other solar system location.

Low-frequency observations from the Moon would open the door on imaging of the regions of particle acceleration in the 2 to 10 solar radii altitudes of the extended solar corona. In this region, the primary radio sources are fast (2–20 keV) electrons from solar flares and suprathermal electrons (~100 eV) accelerated by shocks. The associated radio emissions are called type III bursts and type II bursts, respectively. Both sources produce a plasma instability, which leads to amplification of electrostatic waves, some of which are then converted to electromagnetic (radio) waves. The process takes place at the characteristic frequency of the plasma called the electron plasma frequency; thus, the frequency of the radio emission indicates directly the density of the source, and imaging the radio source would map the extent of the acceleration region.

Methodology and Instrumentation
To make such images at low frequencies, we need to "synthesize" an aperture that is large compared to the wavelengths in question. Large arrays are required to provide the desired angular resolution. An angular resolution of 1 degree at 1 MHz requires a minimum diameter of 15 km. The Moon offers a large, stable surface on which to build a large, capable, low-frequency radio array, for the purpose of imaging solar, heliospheric, and other astrophysical sources at wavelengths that cannot be observed from the Earth's surface.

An array this large can most efficiently be implemented on the Moon in a phased approach, such as:

- Initial test array of 16–32 elements, operated at a number of fixed, narrow-band frequencies, with data downlink to Earth of ~8 Mbps;

- Increasing the size of the array by adding elements. This yields higher angular resolution and better imaging capability. The increased data volume would require more sophisticated onsite data processing to keep the Earth downlink requirement to a reasonable data volume;

- Implementing a second array, to provide full-sky coverage. This array would likely be located on the far side of the Moon, requiring a data downlink relay. An additional advantage of the lunar far-side location is that all interfering terrestrial radio noise is blocked by the Moon.

The major components of the observatory are the antenna array and electric connections, the radio receivers, the central processing unit, the high-gain antenna unit, and the power unit:

Instrument Package	Mass	Power	Telemetry Rate	Heritage
Radio Telescope Array (16–32 elements)	400 kg	500 W	8 Mbps	VLA, FASR

Artist's concept of a radio telescope on the Moon.

The design for the first (test) array would be based on the designs of Earth-based arrays (working at higher frequencies) currently in development. Subsequent deployment of each phase of the observatory would be carried out after several years, permitting one to maximize lessons learned from implementing each phase.

Extent of Astronaut Involvement

Deployment of the initial observatory elements could be done by astronauts, or robotic deployers (which would need to be developed), or both.

Wider Benefits

In addition to images of CME and other solar-related radio emissions, nearly identical equipment could also be used to greatly improve our understanding of the magnetized planets. Earth, Jupiter, Saturn, Uranus, and Neptune all have their main nonthermal emissions from their auroral zones below 10 MHz. Also, imaging emissions from galactic and extragalactic objects in this low-frequency range would open a new window in astrophysics, since there are essentially no existing observations of these objects. In this frequency range, many steep spectra objects like pulsars should dominate the sky and background emissions should exhibit important absorption modifications of the spectrum.

Deployment of
the initial observatory
elements by astronauts

Final stages of the
observatory, probably
robot deployed

4.3 Imaging Geospace from the Moon

Summary

Photon and particle imaging of geospace, the extended region around Earth that includes the ionosphere and magnetosphere, can be accomplished from the lunar surface or from free-flier spacecraft. Such imaging can address several compelling science questions related to large-scale coupling mechanisms between various complex regions in geospace from the ionosphere and extending into the magnetosphere.

Apollo 16 far ultraviolet camera placed on the lunar surface by Astronaut John W. Young.

Value

Global observations of ionospheric and magnetospheric phenomena provide measurements that are key to understanding the hazards and impact of space weather in the regions of space where most space agency, commercial, and military space operations occur. These measurements also provide constraints to global ionospheric and magnetospheric models and provide keys to solving compelling science questions associated with the coupling between the solar wind, magnetosphere, and ionosphere and coupling of the high and mid-equatorial regions of the ionosphere (Meier, 1991; Su et al., 2001).

Description

Imaging of geospace with optical ultraviolet (UV), extreme ultraviolet (EUV), and energetic neutral atom (ENA) instruments from the lunar surface, from lunar orbiting, or from free-flier spacecraft can address several compelling science questions. These include, but are not limited to: large-scale coupling mechanisms between various regions in

geospace from the ionosphere and extending into the magnetosphere (using UV and EUV global images); mesoscale coupling between high, mid, and equatorial regions of the ionosphere (UV images and spectral signatures); large-scale magnetospheric configuration during magnetically disturbed periods (UV, EUV images); development and evolution of ionospheric disturbances that impact communications and GPS signals (UV images); and ring current and plasma sheet dynamics (ENA images). Lunar surface operation enables new opportunities for enhanced communication bandwidth, instrument "staring," and simplified subsystem design owing to the simplicity of fixed site operation when compared to a free-flier.

Methodology and Instrumentation

There are two types of geospace imaging missions that will be enabled by missions to the Moon: (1) those that can best be done from the surface and (2) free-flier or lunar orbiting missions that are enabled by the journey to the Moon.
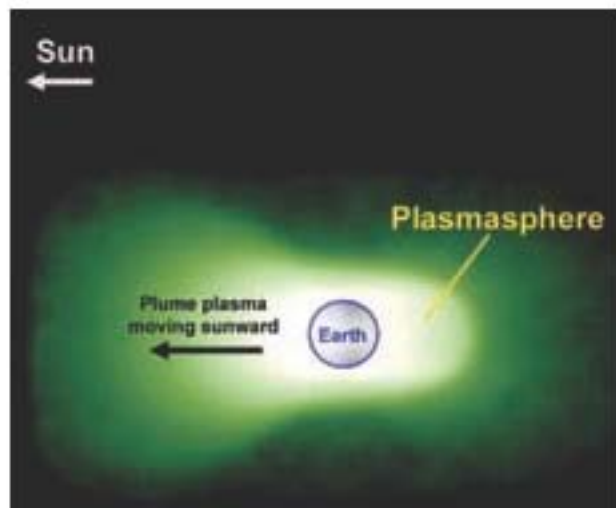
Modeled image of the Earth's extended atmosphere called the plasmasphere as seen from the Moon.

The lunar surface provides a seismically quiet, largely jitter-free platform for the observation of geospace via remote sensing. In particular, far ultraviolet remote sensing from the Moon offers the means to observe the signatures of the energetic and dynamical properties of the ionosphere/thermosphere (IT) system (Carruthers and Page, 1972). The lunar vantage point allows nearly every point on the Earth to be examined at all local solar times during each month, thus removing seasonal effects. Designing a sensor with a spatial

First image of Earth's geocorona and equatorial bands.

Apollo FUV Imaging of the Earth

Dr. George Carruthers of the Naval Research Laboratory developed the Ultraviolet Camera/Spectrograph (UVC) in 1966, using suborbital sounding-rocket flights. Then, on April 21, 1972, during the first lunar walk of the Apollo 16 mission, the astronauts placed the 22-kilogram UVC in the shadow of the lunar module. It was mounted on a tripod and gold-plated to protect it from overheating. In designing the UVC, Carruthers and his team had to consider the stress of the journey and ability of the instrument to function in a vacuum and under low-gravity conditions. It also had to be simple enough for the astronauts to operate. However, Carruthers had solved the most difficult of these problems during his sounding-rocket work. The instrument provided spectroscopic data in Far Ultraviolet (FUV), the wavelength range of 300 to 1350 angstrom units (Å) with a 30-Å resolution.

The UVC was a high priority for Apollo 16 and Carruthers was its principal investigator and chief engineer. The instrument took some 200 UV pictures of 11 selected targets. For the first time, scientists were able to examine large expanses of the Earth's atmosphere for concentrations of pollutants. In a historic picture, using a 20-minute exposure, the UVC provided the first full view of the Earth's hydrogen geocorona, which extends thousands of miles into the far outer atmosphere. It also took the first full images of the outer atmosphere airglow belts of ionized gases that reflect radio waves.

resolution of 10–100 arcseconds is well within our current capabilities. Such a sensor would provide real-time IT specification as well as addressing key, driving science questions about the response of the IT to geomagnetic and solar disturbances. Other sensors could readily be envisioned such as those capable of imaging the geocorona (Carruthers et al., 1976) and the plasmasphere. It may even prove practical to image the polar outflow signatures of some ions.

Small autonomous payloads could be carried out beyond the Earth's gravitational well and deployed via insertion motors (and possible lunar gravitational assist) into orbits that are feasible for some payloads. Because launch payload capacity is discretized, there may be capacity reserved for missions that either are to serve as technology development pathfinders or are too risky to accept (either from a science or technology standpoint) if the launch/mission costs are high. An ENA imager is a good example of an instrument that might be most effectively deployed on a spacecraft while en route to the Moon. This path forward has the advantage of enabling missions that maintain the vitality of geospace science while evolving instrument capabilities and adding to the science return of the broader NASA science program.

For either type of investigation, optical, UV, and particle imaging constitute the likely measurement approach. This includes the following complement of spectrometers and cameras:

| Spectrometer | 15 kg | 25 W | 20 kbps | TIMED |
Visible Camera	10 kg	15 W	10 kbps	Polar
UV Camera	20 kg	25 W	20 kbps	Polar, IMAGE, Viking
EUV Camera	20 kg	20 W	20 kbps	IMAGE
ENA Imager	20 kg	15 W	10 kbps	IMAGE

Extent of Astronaut Involvement

Astronauts can be effectively used to align and position instruments to enable a clear field of view of geospace.

Wider Benefits

There are many benefits to imaging geospace beyond advancing knowledge and understanding of this complex coupled region, such as:

1. The identification and specification of ionospheric structure and irregularities that impact GPS signals, at all scales from 25 km to thousands of kilometers.
2. The identification and tracking of changes in composition that affect the amount of drag seen by satellites in low Earth orbit.
3. The identification of the location of the equatorward edge of the aurora for radio frequency propagation (for both civil aviation and over-the-horizon radar applications).
4. The improved specification of global assimilative models of the upper atmosphere (each image has the equivalent of thousands of ionospheric soundings).
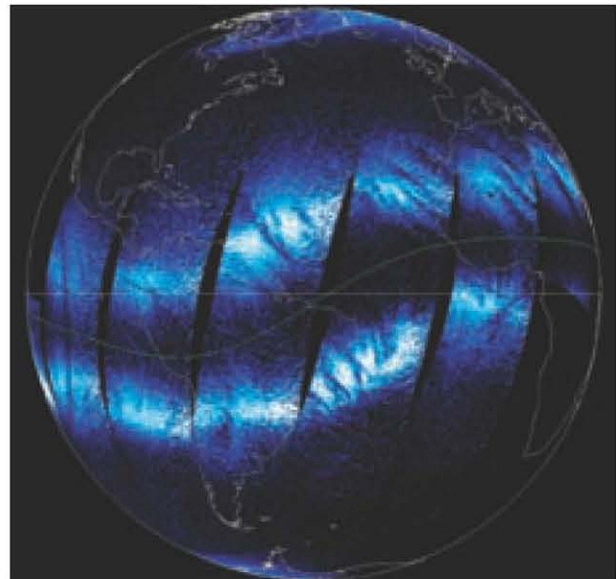
TIMED mission image of equatorial plasma bands in the Earth's ionosphere.

Siting of instruments
by astronauts

41-C mission specialists repair captured Solar Maximum Mission Satellite.

Astronauts Rescue Solar Max Mission

In 1985, the Shuttle Remote Manipulating System (SRMS or Canadarm) was used to rescue the $240M Solar Max satellite. The effective teamwork of Commander Bob Crippen and arm operator Terry Hart along with the astronaut repairmen James van Hoften and George Nelson enabled the satellite to be redeployed the next day to continue its mission to observe solar flares over a wide range of wavelengths in order to understand the trigger mechanism.

In 1997, the Shuttle Pointed Autonomous Research Tool for Astronomy (SPARTAN-201) satellite was retrieved manually and secured by Astronaut Mission Specialists Winston Scott and Takao Doi in a true international collaboration.

4.4 Analyze the Composition of the Solar Wind

Summary

The solar wind reflects the composition of the Sun and physical processes in the corona. Analysis will help differentiate between several theories of solar system formation and physical processes in the solar corona. Ions will be collected on various materials and analyzed on return to Earth. For a good overview, see Wiens (2004) and Geiss (1972).

Value

Similar experiments were first done using foils on Apollo missions. Then, the Genesis mission added to the database, although with some complications due to the hard return of the spacecraft to Earth. Additional data gathered in this very simple and inexpensive experiment during upcoming lunar missions will expand the restricted scientific return of Genesis. Specifically, additional elements and isotopes will be accessible, providing missing information on solar formation and evolution.

It is believed that the highly diverse objects of our solar system originated from a relatively homogeneous solar nebula. Ultimately, the correct theories for the origins of these objects, including planetary atmospheres, will be validated by their predictions of chemical and isotopic compositions relative to the average nebular composition preserved in the surface layers of the Sun.

Description

The basic feasibility of such an experiment has been demonstrated by the short (2–40 hour) exposures of foils during Apollo missions and by the Genesis mission in 2001–2004. Foils were flown on Apollo 11, 12, 14, 15, and 16. The mass for Apollo 16 was 450 g for a foil that was exposed for 45 hours. Net exposure times of several weeks to months were achieved during the Genesis mission. However, much longer exposure times to the solar wind are needed to provide sufficient data to achieve the science objectives.

The proposed experiment provides solar abundances at the level of precision required to discriminate among competing theories. Moreover, the experiment will test fundamental assumptions, such as whether or not solar and nebular compositions are identical.

The experiment will return solar matter for compositional analysis in terrestrial laboratories. Ultra-pure materials, such as those utilized on the Genesis mission, will be exposed to the solar wind for varying periods, under varying solar wind conditions, and at different parts of the solar activity cycle. Average and near-instantaneous solar system isotopic and elemental compositions will be obtained.

The science objectives may be summarized as follows:

• Obtain precise solar isotopic abundances to the highest atomic weights possible. The highest priority is for isotopic compositions of O, N, and noble gases, for interpretation of isotopic variations in meteorites, planetary atmospheres, and lunar samples;

• Obtain solar elemental abundances improved by a factor of 5–20 in accuracy over current measurements.
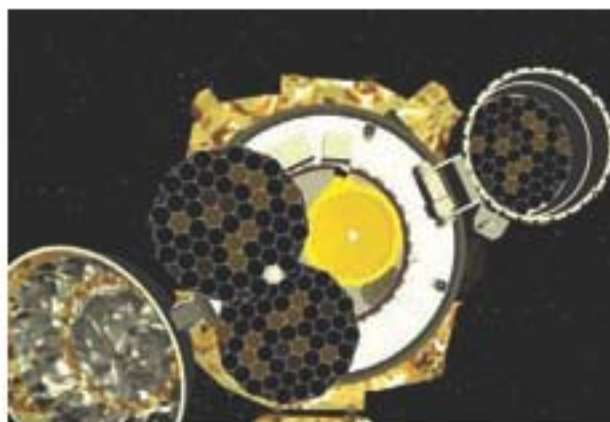

Genesis spacecraft, the modern equivalent of the lunar foils.

Methodology and Instrumentation

Based on the instrumentation for the Genesis mission, requirements are as follows:

Collector Arrays	5 kg	3 W	1 kbps	Genesis
Concentrator	5 kg	3 W	1 kbps	Genesis
Monitors	5 kg	3 W	1 kbps	Genesis

Collector Arrays: These are high purity materials into which solar wind ions are implanted. Different arrays will sample different solar wind regimes, providing information on elemental and isotopic differences between these regimes. This will also help to correct for differences between solar and solar wind abundances. The arrays will be exposed according to information provided by the solar wind monitors.
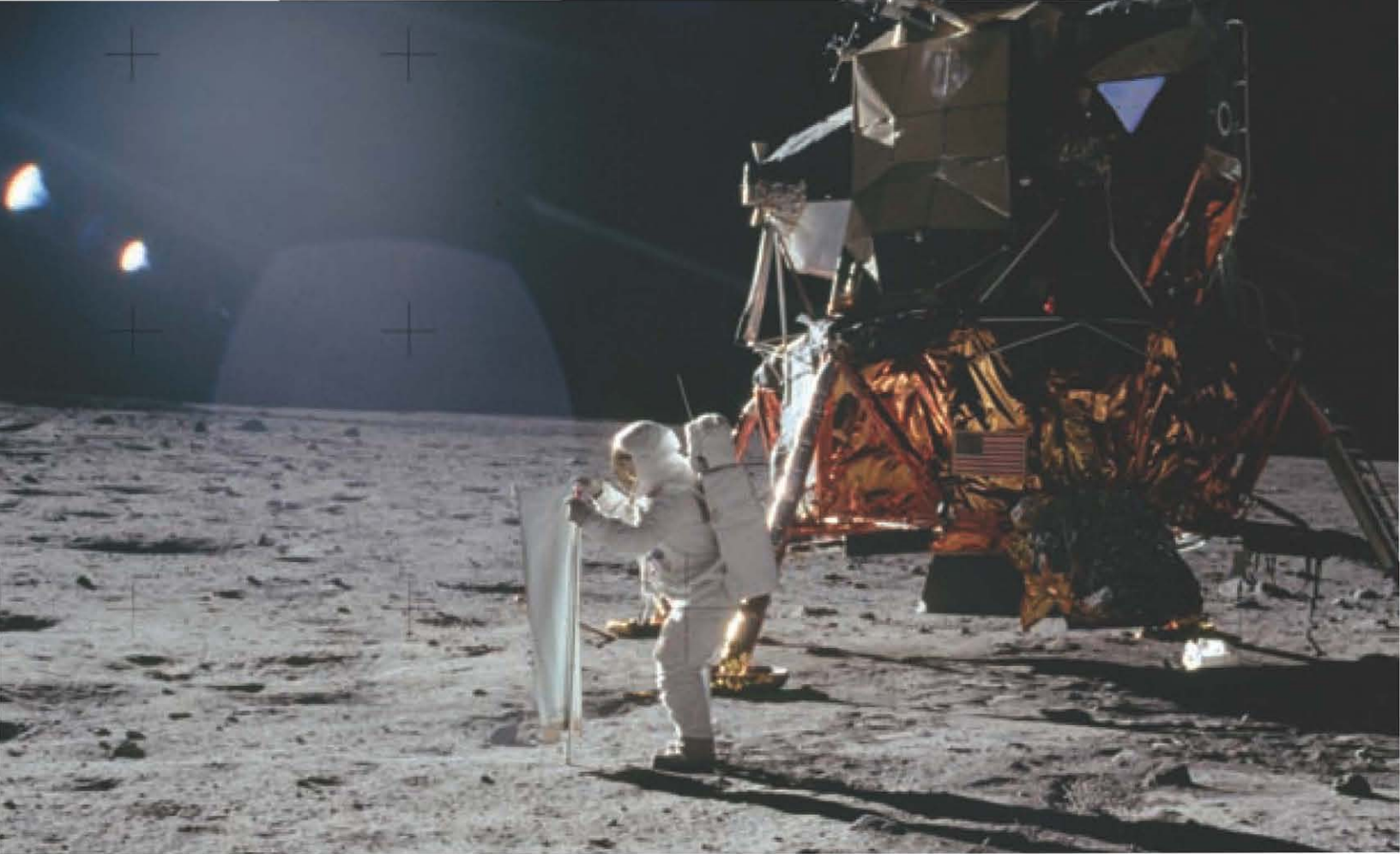
Apollo 11 lunar foils.

Concentrator: An electrostatic mirror that will concentrate, by a factor of at least 20, elements at least up to Ne and preferable to Kr. This is necessary to achieve the needed precision for O and isotope ratios for Kr.

Monitors: Ion and electron electrostatic analyzers will provide the data required to set concentrator voltages and to deploy the appropriate array for the prevailing solar wind regime at the time.

Samples will be analyzed when returned to Earth. The associated laboratory analytical instruments will be patterned after those established for the Genesis samples.

Extent of Astronaut Involvement
These instruments can be set out on the lunar surface, either robotically or by humans. They should remain deployed for months to years, be recovered, and then be returned to Earth. Recovery is probably best done by humans, rather than robotically, in order to assess the condition of the instruments and their environment. Experience has already shown, via Apollo and Genesis, that robotic deployment is feasible and relatively simple. The instruments are small enough that deployment can be done by hand or with the simplest mechanical assist.

Wider Benefits
Results are of importance to numerous studies in stellar astrophysics.

Instruments delivered on the earliest robotic missions to the Moon

Samples to be returned via early human landings

New data can be obtained as state-of-the-art instruments evolve; important results can be replicated

4.5 The Moon as a Base for a High-Energy Optical Solar Observatory

Summary

The Sun can be observed with optical and UV telescopes and coronagraphs, vector magnetographs, and x-ray and gamma-ray imaging spectroscopes from the Moon.

Value

The benefits of the proposed lunar instrumentation are hence twofold: (1) enable fundamental advances in our scientific understanding of the processes that lead to energy release and the acceleration of energetic charged particles by the Sun and hence in other, more distant and more energetic, astrophysical objects; and (2) allow us to further our understanding of the conditions that lead to hazardous eruptive solar events, and hence to provide operationally useful warnings (or "all-clears") to enhance the safety and productivity of manned missions to the Moon and Mars (see Introduction to Theme 2).

Description

Solar flares and CMEs are the most powerful explosions in the solar system. Over a period of minutes, they accelerate copious quantities of electrons, protons, and heavier ions

Owen Garriott performs a spacewalk during the Skylab 3 mission.

Skylab Apollo Mount Solar Telescope

The Apollo Telescope Mount (ATM) on Skylab (1973–1974) was NASA's first full-scale, manned astronomical observatory in space. The ATM is one of the most important milestones in the history of solar astrophysics. In terms of versatility, sensitivity, and reliability, the performance of the ATM telescopes and instruments exceeded the highest aspirations of astronomers. Yet, the mission appeared headed for total and complete disaster, until rescued by the heroic and skillful exploits of the astronauts in repairing the damage incurred by the spacecraft during launch. In this and other ways, the role of man in the operation of space observatories was clearly, even brilliantly, delineated. The study of ATM observations has already led to many new discoveries about the nature of the Sun and about the fascinating events that occur on even a very ordinary star. Especially illuminating has been the recognition of the extent to which the Sun's magnetic field is responsible for the structure, dynamics, and heating of the Sun's outer layers. So massive was the harvest of information that many years of postflight analysis were required to exhaust its findings, which ultimately defined the nature of future solar observatories.

(Miller et al., 1997). Although the physical processes by which this is achieved are not fully understood, the general scientific consensus is that the energy originates in stressed coronal magnetic fields and is released through a process known as magnetic reconnection. Understanding the processes through which magnetic energy is converted into accelerated particles is fundamental to understanding particle acceleration in general, and in particular, in planetary magnetospheres and in other astrophysical sources.

Larger flares are usually associated with CMEs that propagate outwards into the interplanetary medium, producing shock-accelerated particles at their leading edges (Zank et al., 2000). Both particles accelerated directly in the flare and those produced by the CME can have devastating effects on spacecraft instrumentation and on astronauts who are not adequately shielded. The electric and magnetic disturbances caused by the interaction of the CME with the Earth's magnetosphere can create havoc on terrestrial communications and power networks (Joselyn, 1992).

Methodology and Instrumentation
A return to the Moon will permit the construction of telescopes and instrumentation designed to observe the high-energy emissions produced by the Sun during flares and other eruptive events. Although many of the necessary observations can be carried out using free-flying instrumentation, there are some significant advantages to deploying such instrumentation on the lunar surface. Observing from the Moon will permit us to extend the energy range of solar (and cosmic ray) spectra below the energy cutoffs imposed by the Earth's atmosphere and also permit observations to be made free of complicating geomagnetic effects and the day/night observing cycles in all but Sun-synchronous Earth orbits. Further, the Moon, because it is seismically stable and has no wind, provides an exceptionally large and stable platform on which to position observing instrumentation. Deploying instrumentation near the "peaks of eternal light" at the lunar South Pole permits a continuous, unobstructed view of the Sun with relatively constant background. Instrumentation deployed at sortie sites would also be able to observe the Sun for half a lunar day, i.e., ~14 days. Coincidentally, this is also half the solar rotation period, so that a long-lasting solar active region could be observed uninterrupted by night

The proposed instrumentation would be a comprehensive, coordinated package consisting of the following components:

Instrument Package	Mass	Power	Telemetry Rate	Heritage
Soft X-Ray, Hard X-Ray and Gamma-Ray Imagers, Spectrometers, and Imaging Spectrometers (1 keV to >100 MeV)	100 kg	1 kW	100 Mbps	RHESSI
Gamma-Ray Spectrometers (50 keV to 1 GeV)	1000 kg	1 kW	1 Mbps	CGRO
Neutron Spectrometers (10 MeV to >150 MeV)	100 kg	250 W	5 kbps	SONTRAC
Cosmic-Ray Neutron Monitors (measure the spectrum and anisotropy of the cosmic-ray flux)	100 kg	100 W	5 kbps	Mount Washington
Optical/IR Imaging Spectrometers	1 kg	100 W	100 Mbps	BBSO
Optical Interferometers (an array of small, diffraction-limited telescopes)	100 kg	500 W	10 Mbps	–
Optical Vector Magnetographs	10 kg	50 W	100 Mbps	Haleakala, BBSO, MSFC
Optical Coronagraphs	25 kg	100 W	10 Mbps	HAO
Optical, UV, and EUV Spectroheliographs	50 kg	100 W	10 Mbps	Skylab, SoHO
Radio Imaging Spectrometers	50 kg	50 W	10 Mbps	VLA, OVRO
In situ Particle and Field Instrumentation	15 kg	25 W	1 kbps	GOES

or increases in background from its first appearance over the East limb to its disappearance over the West limb some 13 days later. Much of this time would be when the region is most strongly connected magnetically to the Earth-Moon system and so presents the greatest hazards to communications, space-borne instrumentation, and astronaut health in the near-Earth space environment. The slow rotation rate of the Moon also allows horizon occultation measurements (at a drift rate ~0.5 arcseconds/second) to be made at non-polar sortie sites. This would permit the study of fine-scale features in solar active regions.

Together, this complement of instruments will permit a thorough study of the magnetic precursors to solar eruptive events, the particle acceleration processes that occur within the flare itself and at the CME-associated shock, and the relationship between solar conditions and the probability of hazardous particle events at 1 AU. During certain times of the year (depending on planetary alignment), it will also provide important diagnostic information on active regions that pose a hazard for spacecraft en route to, and orbiting, Mars.

To provide nearly continuous coverage, some or all of the instrument packages could be replicated and reside near opposing limbs of the full Moon within contact of ground stations on Earth, thereby enabling quasi-continuous monitoring of solar activity.
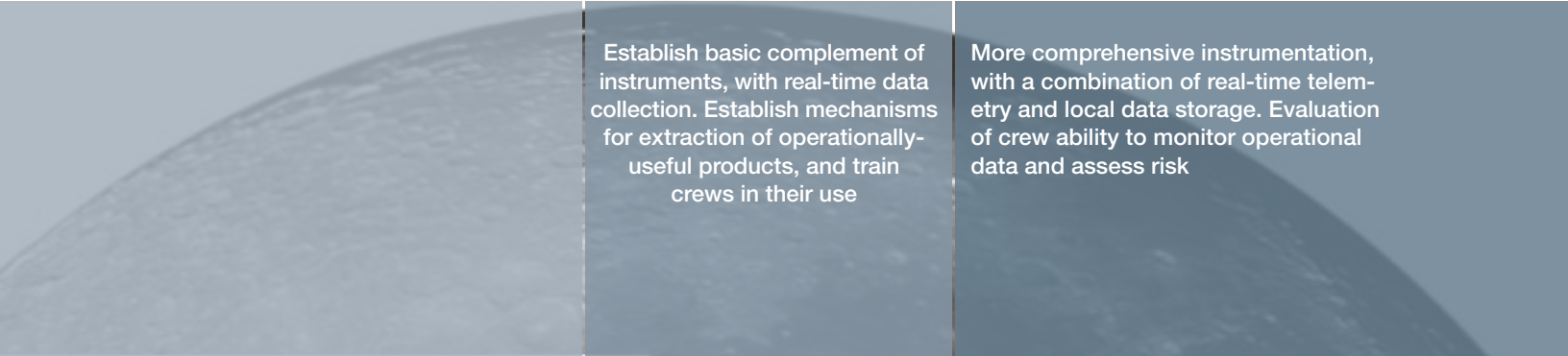
Because of the need to transport such instrumentation to the Moon on a lander spacecraft, typical instruments would have dimensions comparable to those on Earth-orbiting unmanned spacecraft, viz. size from <1 m to ~10 m and mass in the range of 10 kg to 1000 kg. However, these values could be extended through lunar surface assembly of modular subcomponents (e.g., interferometer components). The instrumentation would need <1 kW of power to operate. The large data collection rates (in excess of 10–1000 GB/day) could be accomplished through in situ storage for collection by astronauts on EVA activity and subsequent return to the Earth.

Extent of Astronaut Involvement

For the surface instruments, human involvement is necessary to put the instruments in appropriate locations and possibly to retrieve data on a periodic basis. Real-time analysis of the data to provide operationally-useful products will require the presence of a trained scientist-astronaut. The experiential learning earned during lunar missions will be invaluable for later Mars missions, when real time risk evaluation and operational decisions will have to be made by the crew on the Martian surface independent of ground control at Earth.

Wider Benefits

In addition to providing valuable scientific information on the processes underlying solar activity, the proposed complement of instruments will play a major role in safeguarding astronauts and spacecraft from radiation hazards associated with violent solar activity through the ability to develop real-time reliable forecasting of hazardous radiation events.

Establish basic complement of instruments, with real-time data collection. Establish mechanisms for extraction of operationally-useful products, and train crews in their use

More comprehensive instrumentation, with a combination of real-time telemetry and local data storage. Evaluation of crew ability to monitor operational data and assess risk
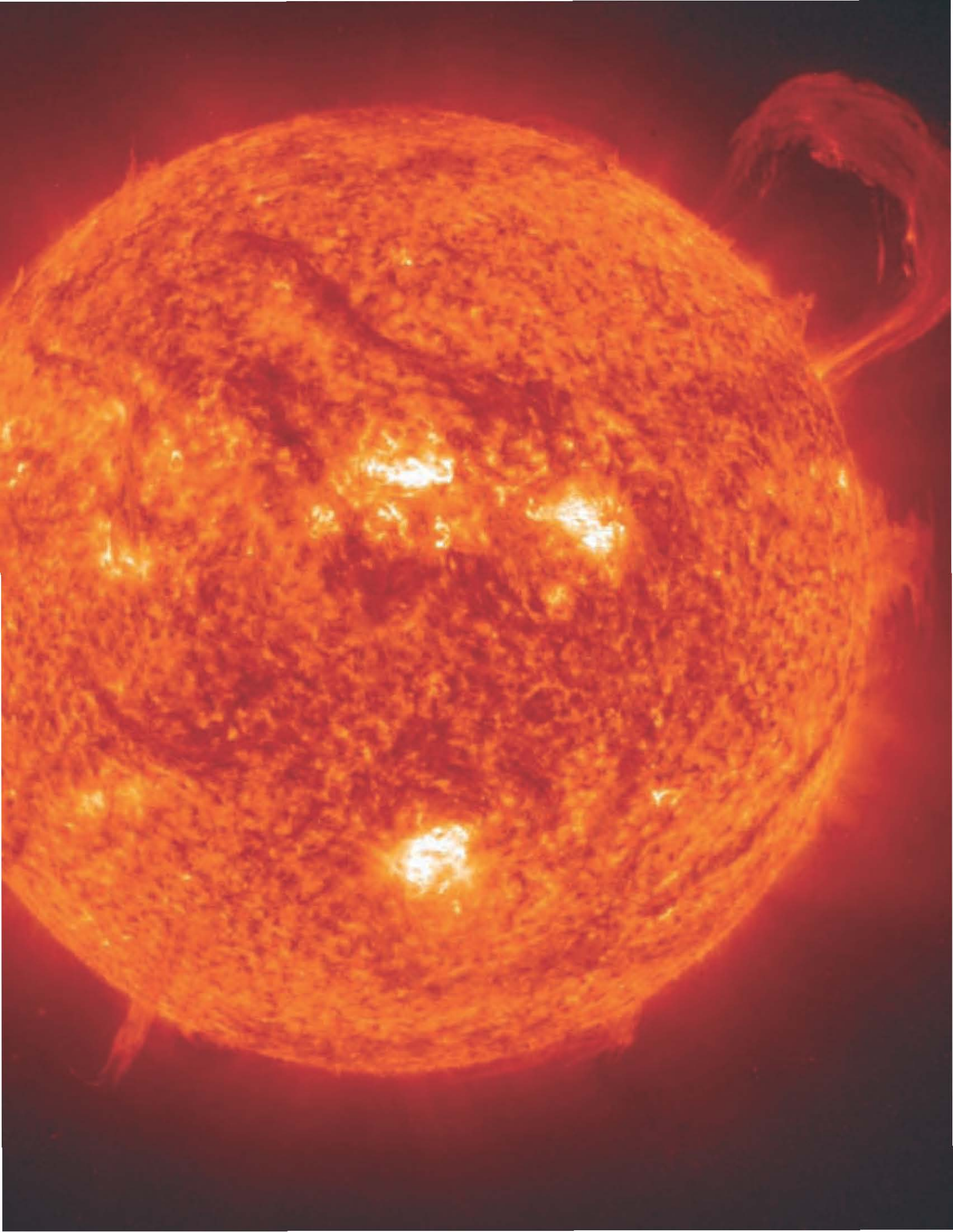
4.6 The Sun's Role in Climate Change

Summary

The whole Earth reflectance is measurable from the Moon for the full range of reflection angles through each lunar month.

Value

In general terms, Earth's climate is driven by the Sun's output, the Earth's reflectance, and thermal emission. Of these three fundamental climate variables, the Earth's reflectance is the least well studied. In fact, variations in reflectance are being implicitly ignored when solar cycle variables are treated as proxies for the net sunlight reaching Earth. This objective is focused on providing important information needed to fully characterize global climate change and the Sun's role.

Currently, the value of Earth's reflectance is a combination of localized measurements and modeling. By measuring the reflectance from the Moon, one can obtain a value for the whole Earth each 24-hour period, and through the lunar month, one can measure the reflection as a function of phase angle. These earthshine observations would provide the most thorough and complete measurements of the Earth's reflectance and its seasonal changes, as well as its longer term evolution.

Description

Variations in the solar irradiance have been precisely measured for more than a quarter century, combining observations from various satellites, and it appears that the Sun's irradiance has climatologically insignificant variations over the solar cycle. These observations do not explain the terrestrial signatures of the solar cycle in climate records. If the recent irradiance variations are typical, the logical effect to search for is a corresponding, or even amplified, solar-driven change in the much less well-studied reflectance of the Earth. Answers here require precise measurements of the global reflectance of the Earth. Several indirect mechanisms have been proposed in the literature to produce such amplification, ranging from changes in EUV radiation tied to ozone, to changes in cosmic rays and atmospheric ionization tied to cloud formation, to changes in storm tracks and atmospheric circulation, or changes in the Earth's global electric circuit. But, so far, the possible causal role of each mechanism remains ambiguous, at best.

The Moon provides a unique platform from which to measure the Earth's reflectance in both high and low resolution, as well as the entire spectrum of solar output from hard x-rays to the infrared and from the various components of the solar wind. Ideally, to determine the Earth's reflectance, it would be necessary to observe reflected radiances from the Earth, from all points on the Earth and at all angles. An Earth-facing part of the edge of the Moon would provide an ideal platform from which to measure the Earth's reflectance. To determine the Bond albedo (reflection in all directions) from earthshine, one would integrate over all phases of the Moon and get a large-scale value for the parts of the Earth contributing to the earthshine. Measuring the resolved earthshine would provide the reflectance for small patches of Earth, which would be of central importance in climate modeling. At present, there is difficulty in treating clouds in climate models, and it is the behavior of clouds that the Intergovernmental Panel on Climate Change (IPCC) says is the greatest uncertainty in climate modeling. The resolved earthshine would provide direct measure of local reflectances/cloud cover. These observations would be an excellent complement to data from satellites in LEO, where determining albedo from the measured radiances is more complicated, because modeling of bi-directional radiative transfer through the atmosphere is required, and that has its own difficulties.

Methodology and Instrumentation

There are two levels of lunar earthshine measurements: unresolved and resolved. Unresolved earthshine measures the Earth as a star. The unresolved earthshine would be seen to vary through 24 hours as the Earth rotates and the Moon's orbital position (read phase angle) changes. The instrument for measuring the unresolved earthshine could be a carefully calibrated diode with a very low telemetry rate just yielding intensity as a function of time. This instrument need not weigh more than 1–2 kg and would require no intervention. The instrument would probably require a shutter to shield it from direct sunlight. Ideally, two of these would be placed on the Moon at opposite ends of a diameter (like Crisium and Grimaldi), so as to cover both positive and negative phase angles of the lunar orbit.

Earth rise as photographed from Apollo 9.

Visible/IR Earth-Observing Camera	10 kg	10 W	15 kbps	
Solar X-ray Spectrometer	5 kg	5 W	5 kbps	GOES SXI
Solar UV Spectrometer	5 kg	5 W	5 kbps	SDO

To resolve the earthshine, which would be essential for direct input to climate modeling, the diode would be replaced by a charge coupled device (CCD) covering the extreme blue to the mid-infrared. Even a small format camera would provide spatial resolution of ~100 miles, which would be useful as essentially direct input to climate models. A small 3-cm-aperture telescope would provide adequate resolution of the Earth. The telemetry would be low, but would depend on the camera format and the time resolution required.

Solar pointing spectrometers would also be needed to provide source input to the climate models. Flight heritage data for an x-ray and UV spectrometer exist that provide needed measurements.

Extent of Astronaut Involvement
The unresolved, Earth-as-a-star observations are so simple with robust hardware that it would be straightforward to set them up robotically. The resolved earthshine would benefit from being set up and run briefly by an astronaut. Nonetheless, the second phase observations could be robotically set in motion.

Wider Benefits
Real-time pictures of the Earth taken from the Moon would capture popular imagination. In addition, many problems ranging from climate change to the origin of the terrestrial footprint of the solar cycle would be addressed.

Earth-as-a-star observations from a very light robotic payload to the Moon

Resolved disk measurements using equipment set up by an astronaut

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