Objective J

Safeguard the
Journey of Exploration

Maximize the safety and productivity of human and robotic explorers by developing the capability to predict the extreme and dynamic conditions in space.

[Facing page? Figure: Robots and People on Mars]
|| [Or Figure: More Robots and People on Mars]

Figure J0: Humans will work with robots and vehicles on Mars. Safe and productive expedition activity will depend on accurate forecasting of surface and space weather conditions that mitigates risks but avoids false alarms

Harsh conditions in the space environment pose significant risks for the journey of exploration. Like seafaring voyagers, space explorers must be constantly aware of the current space weather and be prepared to handle the most extreme conditions that might be encountered. The important considerations include sudden changes in energetic particle and electromagnetic radiation, encounters with plasmas that cause spacecraft charging and discharging, and the uncertain response of neutral atmospheres to variable energy inputs.

The first step toward safeguarding astronauts and robotic assets in space is to characterize the extremes and ranges of variability that can occur in the space environment to help establish appropriate design requirements for vehicles, electronics, and habitats. This requires not only measurements in various locations at different times, but also an understanding of the physical processes that both cause temporal fluctuations and limit the range of responses of the system to those inputs.

The next milestone requires the ability to determine current conditions in key locations from an affordable set of available measurements – nowcasting of the space environment. This provides the critical operational knowledge that productive work can proceed at the time. The set of observations must be carefully chosen and the physical system must be modeled well enough to give confidence that the results can be extrapolated to the relevant location.

Finally, we must develop the capability to forecast the dynamic conditions in space. Forecasting quiet times may be as useful as forecasting disturbances. Initial reliance on empirical relationships will give way to high-fidelity physics. As our understanding of the fundamental processes improves, through comparison of predictive models with reality, we will gradually improve the accuracy and extend the duration of our predictions, and provide key support to implementing the Vision for Space Exploration. As with terrestrial weather in the past several decades, progress will be made, but it will be difficult because the systems are more diverse, the measurements are more sparse, and the physics is more complex.

These steps are not necessarily sequential and some capability already exists in each area. One of the first major challenges is to determine more precisely what capabilities are needed and when. Our Objective J focuses on the science necessary to ensure safety and maximize productivity of both human and robotic space explorers. This objective includes both near-Earth and planetary environments, especially as they affect the robotic and technological systems that support human space flight. Benefits of addressing these issues include the optimization of spacecraft and instrument design, improved planning of mission and operations scenarios, ensuring the safety and maximizing the success and productivity of both robotic and human exploration.

Though much of the dramatic variability in the space environment is driven by solar activity, such as flares and coronal mass ejections or energetic particles accelerated by shocks in the heliosphere, understanding the more routine variations driven by rotation or slowly evolving structures is also important. For example the changing density of the Martian upper atmosphere depends on many uncertain factors in addition to solar activity. The underlying thread that links all three of the SSSC roadmap objectives is working to achieve a detailed understanding of the basic physical processes required to enable prediction. While Objective H focuses on the science needed to understand the processes in the near-Earth space environment that affect life and society, Objective J emphasizes understanding the variability of the space environment and its potential hazards with the purpose of enabling and securing space travel across the inner solar system, which affects primarily astronauts and their supporting assets in space.

Objective J is divided into four priority Research Focus Areas (RFAs). The first aims to adequately characterize the important environments. The second and third build on the first and focus on developing the capability to predict solar activity and understand the propagation and evolution of consequential events in the inner heliosphere. The final RFA will target the environmental variability at planets (Earth and Mars) that impact exploration activities.

[[Thumbnail of Damaged Electronic Components]]

Characterization of Space Environments. RFA J.1 focuses on determining the full range of extreme conditions that may occur in the inhospitable environments that human and robotic explorers will encounter. Learning these limits takes more than just observational surveys; it requires basic understanding of the dynamics of each space environment. This entails developing an understanding of the internal mechanisms, the critical boundary conditions, and the external drivers – the sources of external variability at the Sun and the interplanetary medium which modulates its extremes. This knowledge feeds into the design of safe and productive exploration activities and equipment. Practical understanding of the physical conditions and processes that modulate various space environments will lead to a capability to nowcast and forecast both safe and hazardous intervals.

[[Thumbnail of Filament Eruption]]

Prediction of Hazardous Solar Activity. RFA J.2 aims to develop the capability to forecast solar activity and the onset of the solar disturbances that are sources of potentially hazardous space weather. Successful prediction begins with reliable characterization of impulsive solar disturbances and their global effects on the corona and solar wind through which they propagate. Presently solar flares and CME's are no more predictable than earthquakes or volcanic eruptions. Complex active regions and other features with high potential for eruption can be identified on the visible solar disk and, absent such regions, it is quite feasible to announce “all clear” periods, when sensitive activities can be safely accomplished. However, during most of the 11-year solar activity cycle, when active regions are almost continuously present or could emerge at any time, even short-term forecasting is unreliable with our current level of knowledge. On longer time scales, we need to develop the ability to predict when and where active regions will arise, when the magnetic field will become unstable, and what the heliospheric consequences will be. This requires spacecraft observations of the entire solar surface both to follow the evolution of active regions over the full solar disk and to observe complex active regions that may be magnetically connected to human or robotic explorers far from Earth.

[[Thumbnail of snowed-out LASCO image]]

Propagation to Explorers. Disturbances interact with the solar wind. Particles and fields can be swept up and shocks associated with CME's can accelerate particles to dangerous energies. To maximize the safety and productivity of explorers, we need to develop observational and modeling tools to more accurately predict the arrival times, durations, and severity of solar energetic particle impacts. In addition, exposure to high-energy galactic cosmic rays accumulates over long intervals to dangerous doses. Cosmic rays are modulated by the large-scale field and diverted by disturbances in the outer heliosphere, so they are of less concern during intervals of high solar activity. RFA J.3 entails development of an understanding of heliospheric acceleration mechanisms, the propagation of solar disturbances, and local acceleration of particles by plasma interactions in the disturbed solar wind. All are needed for a practical predictive understanding of these events.

[[Thumbnail of Space Shuttle Re-entry Vapor Trail]]

Space Weather Effects on Planets. Hazards in planetary environments must be understood, characterized, and mitigated to make human and robotic exploration safe, productive, and affordable. RFA J.4 targets how space weather impacts planetary environments in ways that affect exploration activities, such as spacecraft staging in low Earth orbit, or entry, descent, and landing (EDL) at Earth and Mars. Reliable communications and navigation for spacecraft and surface crews will require improved understanding of Earth’s and Martian ionospheres. While the Sun and its variability drive these environments, many internal processes must also be understood. Planetary space weather develops through the interaction of the solar wind with the planetary magnetic fields and plasmas, the interaction of solar photons with plasma and neutral gas populations, interactions with the lower atmosphere, and via internal processes such as dynamos, wave interactions, magnetic reconnection, electric fields, transport, and chemistry. Because geospace is the site of initial staging activities and transport of human and robotic explorers, as well as their return to Earth, understanding this environment is particularly important.

[[[the following is already in a box]]]

Priority Research Focus Areas

- J.1 Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers.

- J.2 Develop the capability to predict the origin and onset of solar activity and disturbances associated with potentially hazardous space weather events.

- J.3 Develop the capability to predict the propagation and evolution of solar disturbances (including shocks, and the acceleration and transport of energetic particles from solar, interplanetary, and galactic sources) to enable safe travel for human and robotic explorers.

- J.4 Understand and characterize the space weather effects on and within planetary environments to minimize risk in exploration activities.

Research Focus Area J1: Characterize the variability, extremes, and boundary conditions of the space environments that will be encountered by human and robotic explorers.

[Figure: Radiation Dose]

[[Figure J1: The radiation dose to astronauts during the Apollo era missions is plotted with the sunspot count. This plot graphically highlights the profound difference between short Apollo-like expeditions to the Moon and the longer duration stays anticipated as part of the Vision for Space Exploration, where sporadic risks will become certain events.]]

Mitigating future risks to long-duration space flight requires knowledge of two elements for operational planning: the anticipated background environment and the worst-case transient event environment. The primary goal of space environment characterization is to establish the range of variability both for system design purposes as well as to develop and refine comprehensive models for predictive capabilities. This characterization must be conducted over a sufficiently long time frame. We also need to be able to nowcast the space environment in real time, so astronaut explorers can react to current conditions.

Energetic particles from the Sun generally propagate along the spiral magnetic field embedded in the solar wind. However, CMEs routinely disrupt the field lines and solar wind flow. Further complicating our understanding of this relatively straightforward view are recent observations of significantly elevated proton levels without any activity observed on the Earth-facing side of Sun. Activity on the far side of Sun can have effects throughout the inner heliosphere. Future spacecraft in transit to Mars will undergo a 6-9 month cruise phases far from either Earth or Mars, requiring the support, characterization and forecasting capability from their own, remote location, independent of Earth-local forecasting. Measurements from a wide range of longitudes will be required to accurately characterize, and ultimately predict the conditions throughout this region of the inner solar system.

Understanding the near-Sun source region of the space environment is ultimately required to provide the boundary conditions to enable accurate predictive modeling. This region produces solar energetic particles with energies as high as 1 GeV/nucleon. Beyond ≈15 Rs from the Sun, the solar wind speed is higher than any of the embedded wave speeds, so it is not possible to extrapolate back from *in situ* measurements made outside this region to determine the physical mechanisms at work there. A near-Sun mission is the only way to provide the direct observations necessary to understand the physics of this critical region.

The continuous galactic cosmic ray background radiation is modulated by the heliosphere. Progress in understanding the modulation requires measurements far from the ecliptic plane and from the inner and outer reaches of the heliosphere.

Characterizing the hazardous radiation environments within the Earth's magnetosphere is also an integral part of safeguarding the journey of exploration. For example, currently we do not understand the formation of new radiation belts.

Three investigations are associated with this RFA.

Investigation J1.1 - What is the variability and extremes (worst case) of the radiation and space environment that will be encountered by future human and robotic explorers, both in space and on the surface of target bodies?

Future enabling missions: THEMIS, RBSP, ITSP, IH Sentinels, SWB, L1/HelioStorm, MSL, LRO

SSSC Great Observatory missions supporting this investigation include: ACE, Wind, Polar, Cluster, TIMED

Investigation J1.2 - How does the radiation environment vary as a function of time and position, and how should it be sampled to provide situational awareness for future human explorers?

Future enabling missions: SWB, IH Sentinels, L1/Heliostorm, Solar Probe, MARS, MMS, RBSP

SSSC Great Observatory missions supporting this investigation include: ACE, Wind, Ulysses

Investigation J1.3 - What is the relative contribution to the space radiation environment from solar energetic particles and galactic cosmic rays and how does this balance vary in time?

Future enabling missions: IH Sentinels, L1/Heliostorm, SWB, Solar Probe, MARS, Telemachus, Solar Orbiter

SSSC Great Observatory missions supporting this investigation include: ACE, Wind, SOHO, ULYSSES, Voyager

Research Focus Area J2: Develop the capability to predict the origin and onset of solar activity and disturbances associated with potentially hazardous space weather events.

[Figure: Silhouette against the Sun]

[[Figure J2: Showing an active Sun with numerous active regions that are likely to erupt and produce hazardous heliospheric conditions.]]

The energetic particles in impulsive solar particle events produced near the Sun by flares or by CMEs in the low corona have 1 AU transit times of minutes to hours, whereas the gradual events associated with interplanetary CME shocks arrive hours or days later. It may be possible to use coronagraph observations of a CME leaving the Sun to give 1-2 day warning of the gradual events, but to give warning of the near-relativistic impulsive events, or to increase the warning time of CMEs and gradual events, it is necessary to develop the capability to forecast the origin and onset of solar activity and disturbances from observations of the Sun itself. Successful forecasting of space weather requires knowledge of solar disturbances as well as the global corona and solar wind through which they propagate. This RFA focuses on the *onset* of solar activity; the next RFA focuses on the *propagation* of the solar disturbances.

We already have some empirical understanding of the regions that generate solar activity: large, complex active regions are likely to produce flares and CMEs. Both are driven by magnetic energy release, but neither the stabilizing mechanism allowing energy to accumulate, nor the release processes are understood well enough to predict eruption reliably. At present, the best indicators of oncoming geoeffective coronal disturbances are morphological. New physical diagnostic measurements in the photosphere, sub-photosphere, and solar atmosphere may hold the key to more reliable prediction. We need to develop the ability to predict the evolution of active regions and CME-producing regions from observations of the solar and corona magnetic fields. We need to understand how changes in the magnetic configurations lead to flares and CMEs.

Another critical need for exploration will be the capability of predicting “all clear” periods when extravehicular activities (EVAs) can be safely accomplished. This will require spacecraft observations of the entire solar surface, both to follow the evolution of active regions that are otherwise hidden on the back side of Sun and to observe complex active regions that may be magnetically connected to human or robotic explorers far from the Earth-Sun line. On a longer time scale, we need to develop the ability to predict the when and where active regions will arise. This will require development of helioseismology techniques and also observation of the Sun from multiple view points. Research focus areas from Objective F provide the foundation for understanding the fundamental processes related to long term variations in solar activity.

In order to develop the methodology and tools required during the first human exploration operations on the Moon, currently scheduled near the solar maximum of 2020, these investigations need to begin at or just after the time of the next solar maximum (2011-2015).

Three investigations are associated with this RFA.

Investigation J2.1 - What are the observational precursors and magnetic configurations that lead to CMEs and other solar disturbances, and what determines their magnitude and energetic particle output?

Future enabling missions: STEREO, IH Sentinels, SEPM, Doppler, SHIELDS, RAM

SSSC Great Observatory missions supporting this investigation include: SOHO

Investigation J2.2. - What heliospheric observations and empirical models are needed to enhance the predictive capability required by future human and robotic explores?

Future enabling missions: IH Sentinels, SEPM, Solar Probe, SWB, L1/ HelioStorms, ADAM, LRO, RBSP, ITSP+ITImager, GEMINI, MagCon, MMS, THEMIS STEREO

SSSC Great Observatory missions supporting this investigation include: ACE, Wind, SOHO, Polar, TIMED, Cluster

Research Focus Area J.3: Develop the capability to predict the propagation and evolution of solar disturbances to enable safe travel for human and robotic explorers.

[Figure: Simulated CME]

Figure J3: A simulated visualization of a Coronal Mass Ejection as it begins to engulf the magnetosphere of Earth, which is expanded in the inset figure. CMEs and high speed solar wind streams drive a large fraction of the space weather effects in geospace because they carry large deflections of the interplanetary magnetic field along with strong enhancements of the dynamic pressure of the solar wind. These effects simultaneously compress the magnetosphere, produce large amounts of ionospheric heating and outflow into geospace, and excite strong circulation of plasma from the magnetotail through the magnetosphere toward the subsolar magnetopause, accelerating energetic particles within the magnetosphere.

Predicting the heliospheric radiation environment requires an understanding of how solar energetic particles (SEPs) are produced, how solar disturbances evolve as they propagate outward, and how solar disturbances modulate galactic cosmic rays (GCRs). The investigations described below, along with the fundamental physical understanding provided by the Objective F investigations, are the necessary steps required for transitioning to predictive understanding.

Solar energetic particles (SEPs) can be grouped into two classes: impulsive events and gradual events. Impulsive events are associated with flares or current sheets in CME's. Gradual events are associated with CME shocks and some are produced farther out in the heliosphere by corotating interaction regions (CIRs). Gradual events produce greater risks to explorers because they extend tens of degrees in latitude and longitude and can last for days as a disturbance propagates through the interplanetary medium. We must characterize the coronal and interplanetary SEP source regions and the properties of the resulting SEPs in order to understand the important factors that determine their composition, flux, energy spectrum, and duration. In situ measurements within 0.3 AU are needed in order to characterize the particles before they are scattered in the interplanetary medium.

The evolution of solar disturbances depends on the pre-existing state of the solar wind and the background magnetic fields through which they propagate. Knowledge of the bulk properties of the solar wind is important for determining the strengths of shocks involved in energetic particle acceleration. On smaller spatial scales, wave turbulence processes play a role in particle heating and acceleration. *In situ* measurements taken more than about 0.1 AU from the Sun cannot be extrapolated back to determine the physical mechanisms at work in the coronal source regions. Remote sensing measurements, both spectroscopic and imaging, can tell us much about the region nearest the Sun. However the regions of the outer corona that provide the interface between the inner corona and the heliosphere (solar wind) are best studied with direct *in situ* measurements. Understanding the physics of these critical regions is necessary to predict the radiation environment throughout the solar system.

Galactic cosmic rays (GCRs) and other energetic particles are affected by disturbances in the heliosphere. The outer heliosphere shields us from much of the nearly continuous GCR flux, as much as 90% at 100 MeV/nucleon. The remaining flux is modulated by variations in heliospheric structure over the solar cycle and by sporadic events such as coronal mass ejections (CMEs). Near Earth substantial variability (factors of up to 10 over the solar cycle) is observed in the differential fluxes of GCRs with energies below several hundred MeV/nucleon. The modulation is not completely understood. Global measurements of the heliospheric structure with concurrent measurements of *in situ* energetic particle fluxes are needed. In particular, missions that travel outside of the ecliptic plane and to the inner and outer reaches of the heliosphere provide essential boundary conditions necessary to constrain models.

Three investigations are associated with this RFA:

Investigation J3.1 - How are Solar Energetic Particles (SEPs) created and how do they evolve from their coronal source regions into interplanetary space?

Future enabling missions: IH Sentinels, SEPM, SWB, DOPPLER, SIRA, Solar Probe, STEREO, L1/HelioStorm

SSSC Great Observatory missions supporting this investigation include: ACE, WIND, RHESSI, SOHO, Ulysses

Investigation J3.2 - How do solar magnetic fields and solar wind plasma connect to the inner heliosphere and what is the nature of the near-Sun solar wind through which solar disturbances propagate?

Future enabling missions: Solar Probe, IH Sentinels, SEPM, STEREO, DOPPLER, Solar Orbiter

SSSC Great Observatory missions supporting this investigation include: SOHO

Investigation J3.3 - How are energetic particles modulated by large-scale structures in the heliosphere (magnetic fields throughout the solar system) and what determines the variations in the observed particle fluxes?

Future enabling missions: STEREO, IH Sentinels, MMS, MagCon, SWB, L1/HelioStorm

SSSC Great Observatory missions supporting this investigation include: Ulysses, Wind, ACE

Research Focus Area J4: Understand and characterize the space weather effects on and within planetary environments to minimize risk in exploration activities.

[Figure of Theremospheric Density

Figure J4: The atmospheric density encountered by the MGS mission during its aerobraking phase. The density varied by an order of magnitude relative to the predictions, illustrating why current atmospheric prediction science makes for a very tricky science of aerobraking and aerocapture. MGS required far more thruster operation than anticipated, as a result of this uncertainty in atmospheric drag, and may have suffered minor damage to appendages. Human landings on Mars will require significantly better knowledge of its atmospheric structure and dynamics to minimize fuel consumption while assuring safety.

Human and robotic exploration of our solar system will necessarily be influenced by the planetary environments encountered. Both the plasma and neutral atmospheres of the planets, including Earth and Mars, impact the safety and productivity of exploration activities. Surface-to-orbit and surface-to-surface communications depend on space plasma variability. Spacecraft control in low orbits and aerobraking parking orbits depend on the upper atmospheric density. Asset staging and operations, as well as astronaut health and safety, are impacted by planetary radiation environments. The radiation environment at the Moon varies as it traverses in and out of the Earth's magnetosphere. The plasma and ultraviolet radiation environment at the Moon's surface contributes to the known problem of lunar dust grain adhesion to space suits and particulate contamination of instrumentation.

Planetary environmental conditions develop through the interaction of the solar wind with the planetary magnetic fields and plasmas as well as through the interaction of solar photons with plasma and neutral populations and with the atmosphere below. To understand the planetary conditions essential for exploration, scientific investigations target the "near-planet" environments of the Earth and other planetary systems. Because initial staging activities and transit of human and robotic explorers will occur in geospace, including at the Moon, understanding of this environment is particularly important (Investigation J.4.1). Furthermore, near-Earth characterization and understanding provides an essential baseline for modeling the impact of space weather in other planetary environments. As exploration proceeds at other planets, our understanding of the near-Earth environment will guide the development of follow-on planetary missions. In addition, comparison with other planetary environments will inform our understanding of our home planet. Understanding and characterizing the effects of near planet interactions and environments is essential to maximize the safety, productivity, and risk mitigation of hazardous conditions for exploration activities. A manned mission to Mars will require some combination of both orbiting and landing crews. Improved knowledge of the Mars atmosphere for aerocapture, entry, descent, and landing (Investigation J.4.2), improved knowledge of densities in the aerobraking regime (90 - 170 km), and in a possible low-altitude (200-300 km) station orbit are all required for safe operation of spacecraft.

Reliable communications and navigation between orbiting and surface crews, and with Earth, are essential, requiring improved understanding of the Martian ionosphere (Investigation J.4.3). Neutral density variability at aerobraking altitudes is predominantly controlled by dynamical influences from below and can be addressed by extending the same basic connections and measurements to higher altitudes.

Orbiting crews may be affected by various space weather effects involving interaction between the solar wind and the partially-magnetized ionosphere and exosphere of Mars. For example, energetic particle events are of concern for astronaut safety, and the variability of radiation dosage when at the surface is poorly constrained (Investigation J.4.4).

The lunar surface that is encountered by the human and robotic explorers contains fine dust grains. Due to the lack of any appreciable atmosphere, the grains are exposed to a plasma and solar ultraviolet radiation environment. This creates a known problem of dust grain adhesion on astronaut suits and instrumentation that is not fully understood or resolved (Investigation J.4.5).

Five investigations are associated with this RFA.

Investigation J4.1 - To what extent does the hazardous near-Earth radiation environment impact the safety and productivity of human and robotic explorers?

Future enabling missions: THEMIS, MMS, RBSP, MagCon, IMC, GEC, AAMP, ITSP, L1/HelioStorm

SSSC Great Observatory missions supporting this investigation include: Polar, ACE, Wind, Geotail

Investigation J4.2 - What level of characterization and understanding of the dynamics of the atmosphere is necessary to ensure safe aerobraking, aerocapture and EDL operations at Mars?

Future enabling missions: GEC, C/NOFS, ADAM, MARS, ITM-Waves

SSSC Great Observatory missions supporting this investigation include: TIMED

Investigation J4.3 - To what extent does ionospheric instability, seasonal and solar induced variability affect communication system requirements and operation at Earth and Mars?

Future enabling missions: CNOFS, ITSP+IT Imager, L1/HelioStorm, ADAM, MARS

SSSC Great Observatory missions supporting this investigation include: TIMED

Investigation J4.4 - What is the effect of energetic particle radiation on the chemistry and the energy balance of the Martian atmosphere?

Future enabling missions: AIM, MSL, ADAM, MARS, Mars GOES, GEC, SECEP, ITMC

SSSC Great Observatory missions supporting this investigation include: TIMED

Investigation J4.5 - What are the dominant mechanisms of dust charging and transport on the Moon and Mars that impact human and robotic safety and productivity?

Future enabling missions: ADAM, MARS, Mars Goes, LRO, plus Moon and Mars Landers and Rovers, Laboratory SR&T program