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Recommendations of the

NASA Sun-Solar System Connection

Radiation Working Group Report

July 2005

“We do not know where this journey will end, yet we know this: Human beings are headed into the cosmos.”

President Bush used these words to herald a refocusing of NASA’s broad range of research and engineering thrusts towards the human and robotic exploration of the Moon, Mars, and possibly additional solar system bodies.

RECOMMENDATIONS OF THE APRIL 2004 NASA SUN-EARTH CONNECTION RADIATION TASK GROUP WORKSHOP

This report was prepared and approved by the following members of the workshop panel:

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"Consider our state of ability to understand and predict the radiation environment to be encountered in the Agency's initiative to conduct a sustained program of human and robotic exploration. What is planned for the period of time of interest? What is missing? What is the next thing to be done?"

R.R. Fisher , NASA's Sun-Solar System Connection (SSSC, formerly Sun-Earth Connection) Division

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PREFACE

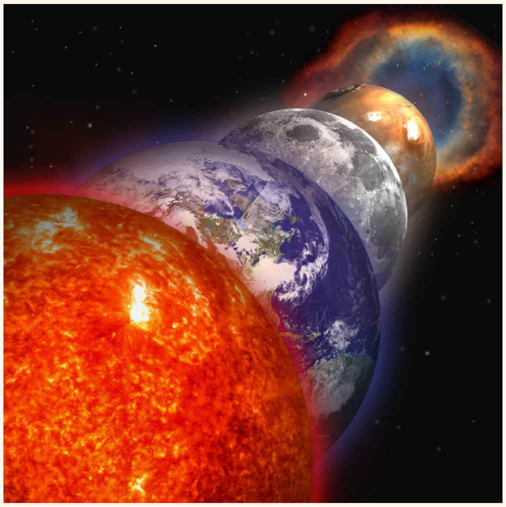
Managers with NASA's Sun-Solar System Connection (SSSC, formerly Sun-Earth Connection) Division organized a brief, targeted workshop to examine existing and planned science missions which contribute to the enabling of proposed manned lunar and Mars missions. The specific charter of the group was outlined by Division Director R.R. Fisher: "Consider our state of ability to understand and predict the radiation environment to be encountered in the Agency's initiative to conduct a sustained program of human and robotic exploration. What is planned for the period of time of interest? What is missing? What is the next thing to be done?" The workshop was held April 5-6, 2004 at the Loews L'Enfant Plaza Hotel in Washington, D.C. Invited workshop attendees, listed in appendix A, represent expertise in a broad range of space weather and human radiation protection science and operational support elements involved in planning, designing, and executing manned exploration missions.

This report provides a synopsis of the state-of-the-art of the space weather elements, particularly in regard to the radiation environment as it relates to manned exploration missions.

CLARIFICATION ON NOMENCLATURE AND TERMINOLOGY

Soon after the conclusion of the workshop, and prior to the completion of this report, NASA Headquarters underwent a reorganization to provide better alignment with the new agency goals emerging from the firmament of the Vision for Space Exploration. The timing of the reorganization led to some confusion in the report's nomenclature. The Sun-Earth Connections (SEC) Division is the original sponsor of the workshop. Dr. Richard Fisher, Chief of the SEC Division, was the intended recipient of this report. As a result of the reorganization, SEC was merged with other groups in the former Office of Space Sciences to form the Sun-Solar System Connection (SSSC) Branch within the Earth-Sun Systems Division, Science Mission Directorate. For the purposes of this report, all references to the (former) Sun-Earth Connection (SEC) Division's programs and missions have been updated to the current organizational structure--Sun-Solar System Connection (SSSC). Dr. Fisher, as Deputy Director of the Earth-Sun Systems Division, remains the reports recipient.

While the original stated purpose of the workshop was to examine support for future human exploration missions by activities under the Living With a Star (LWS) program, discussions of measurement and data analysis requirements expanded to include current and past missions developed under other programs, such as Explorer and International Solar-Terrestrial Probes (ISTP). While these distinctions may be important from some programmatic perspective, from a scientific perspective all past, current, and future space and solar physics missions were considered together, regardless of programmatic origin. To increase the clarity of this report, all of these missions are simply identified by the generic programmatic term "Sun-Solar System Connection (SSSC) missions."



Vision for Space Exploration:
Sun, Earth, Moon, Mars, and Beyond

A CAUTION IN INTERPRETING THIS REPORT

The charge to workshop members focused on a narrow question —which aspects of the program contribute to the enabling of manned exploration missions with respect to the radiation environment. As such, this workshop was not designed to examine the entire SSSC program—only the subset related to manned exploration spaceflight. With this intent in mind, elements of the program not directly related to exploration-class missions, such as geomagnetospheric physics and the trapped radiation belts, ionospheric physics, and the mass-energy coupling between the magnetosphere, ionosphere, and thermosphere, were not examined. Inclusion or exclusion from this report of a particular science element or mission is not to be construed as an indication of the overall importance of the element. The scope and priorities of various science elements within the program have already been established by science and mission definition teams—nothing in this report is meant to supplant the comprehensive results produced by those teams.

EXECUTIVE SUMMARY

In January, 2004, The President announced a redirecting and refocusing of NASA's strategic goals toward a "Vision for Space Exploration." This initiative seeks to dramatically expand NASA's human exploration from low-Earth orbit to the lunar surface as early as the year 2015, and then push beyond to Mars and other solar system bodies. In response, the NASA Sun Solar System Connection (SSSC, formerly known as Sun-Earth Connection (SEC)) program is examining its portfolio of science missions and its other programs. The mutual interests of SSSC science and support of human exploration missions come together in space weather and climatology and their impacts on astronaut radiation exposure, spacecraft shielding, and on operational systems that support human and robotic missions. The Director of the former Sun-Earth Connections Division convened a workshop on April 5-6, 2004, in Washington, D.C., of space weather, space radiation, space physics, solar physicists, engineers, and other experts. Their goal was to identify the elements of the current and planned SSSC program contributing toward enabling human exploration missions and to identify the critical exploration-enabling science areas under SSSC's purview but not addressed by the current program. Attendees represented expertise in space weather and human radiation protection science as well as operational support elements involved in planning, designing, and executing manned exploration missions.

This report discusses highlights and recommendations from the workshop including: a synopsis of the state-of-the-art of space weather elements, particularly the radiation environment as related to manned exploration missions; research needs related to understanding and forecasting galactic cosmic ray (GCR) exposures and solar particle events (SPEs); specific in-situ measurement requirements and the infrastructure necessary to carry-out the measurement program; and recommendations regarding roles of current and planned SSSC space missions.

A host of other issues, most notably radiobiological effects and potential mitigation techniques (which play an even more important role than physical factors in determining the risk from space radiation exposure) were not examined during this workshop. Also excluded were exposures from potential nuclear power sources and the environmental impact to electronic parts and systems, surface materials, etc.

The threat to astronauts from radiation is substantial and well-documented. Astronaut space radiation exposures during exploration-type missions, and the methods to control and reduce them, depend on many physical factors such as mission duration, the amount of shielding available during transit phases and while on the lunar or Martian surface, etc. Each of these factors has a varying degree of importance to astronauts' exposures depending on the type of mission. To help establish priorities, the workshop members considered these factors in the broad context of two mission classes: (a) those involving multiple missions to the lunar surface over an extended period of time and (b) a (temporary) manned exploration of Mars.

Using these assumptions, astronaut radiation exposure concerns result from GCR and large (1 in 10 years) solar particle events (SPEs). We also assumed that transit of the geomagnetically trapped radiation belts would be rapid, as in the Apollo program, and in this case, the exposure to crews from trapped radiation is small compared to the expected total GCR and SPE exposures.

The workshop group recognized the unique position of the SSSC program to provide support towards enabling the successful return of humans to the Moon and the eventual human exploration of Mars. SSSC's research program and assets are an integral component of the toolkit NASA must use to confront the health risks from exposure to space radiation during exploration missions. SSSC's potential contributions in this regard fall into two categories:

- providing the measurements and physical understanding to enable the incorporation of prudent and efficient radiation protection strategies into the design of crew vehicles and mission plans;
- providing the physical understanding necessary for the development of operational radiation protection techniques and tools that will be used by flight support personnel during periods of high space weather activity.

Overall Recommendations

Central to supporting spacecraft/habitat design and operational mission phases is the development/completion of state-of-the-art space environment models capable of quantitatively describing the current state and future evolution of the inner heliosphere and its charged particle environment. As humans venture away from Earth orbit for the first time, it will be necessary to have models that can forecast space weather throughout the heliosphere and not just along the Earth-Sun line.

The minimum conditions necessary to generate these advanced models are simultaneous radiation environment measurements from: the first Lagrangian point (L1), from points closer to the Sun as well as lunar and Martian orbits, and supplemented by data from other heliospheric locations. Data from multiple spacecraft are needed to understand the longitudinal and radial developments of solar particle events, and measurements closer to the Sun can provide ground truth on the conditions under which solar particles are accelerated and transported. Providing these measurements will require a coherent infrastructure of instruments to be developed and put into place in the near-to-mid term. Such an infrastructure is analogous to deploying remote weather stations and new weather satellites to support the exploration and development of remote corners of the Earth. The finite lifetime of space-based observatories and sensors and the long-term nature of NASA's exploration goals mandate that this be an essentially permanent infrastructure investment. These new measurements must be supplemented by the continued analysis of the rich treasure trove of existing space environment measurements in order to gain adequate samples of extreme solar events and to understand the timescales of GCR intensity fluctuation.

Although current plans envision the first human exploration missions 10-15 years in the future, SSSC's support should begin immediately through the continuation of on-going synoptic charged particle and plasma measurements by the ACE, Ulysses, Wind, and Voyager spacecraft. For the longer-term, the SSSC program must ensure that the STEREO and SDO missions be kept on their current schedules. SSSC should also seriously consider scheduling the Solar Sentinels program so that the mission's spacecraft are operating by the next solar maximum.

In terms of enabling the new strategic vision, the most notable gap in the current SSSC program is the lack of space plasma and energetic charged particle observations upstream of Earth in the mid-to-long term. Measurements from these observations provide the context for understanding, comparing, and inter-relating all other (recent) past, current and future space radiation measurements. For the past seven years these data have been provided nearly continuously by the ACE spacecraft and may continue for another 5-10 years. At some point, however, ACE data collection will stop. The SSSC program should begin investigating now options to continue making these measurements beyond the ACE era.

BACKGROUND

The aging of the Space Shuttle fleet, the decreasing number of available Shuttles, and the approaching completion of International Space Station construction spurred a need for a reassessment of NASA's strategic plans.

"We do not know where this journey will end, yet we know this: Human beings are headed into the cosmos." Almost one year to the day following the loss of the Space Shuttle Columbia and her crew, President Bush used these words to herald a refocusing of NASA's broad range of research and engineering thrusts towards the human and robotic exploration of the Moon, Mars, and possibly additional solar system bodies. This new "Vision for Space Exploration" specifies manned lunar missions by 2020, with extended human missions as early as 2015. NASA has immediately undertaken a process to define the overarching requirements to achieve these ambitious goals, and has begun cascading the requirements down to the functional levels of its various enterprises.

In anticipation of these new requirements, the NASA Sun-Solar System Connection Division (SSSC) program is proactively examining its portfolio of current and planned science missions and its other programs in the context of supporting future human and robotic exploration missions. An immediate apparent overlap of SSSC science and support of human exploration missions is space weather and climatology and its impact on astronaut radiation exposure, human support, and spacecraft shielding design.

INTRODUCTION

In the autumn of 1367, the citizens of Florence, Italy, by public vote, endorsed a radical vision. Their new church, designed in addition to the worship of God as a reflection of the importance and power of their city, would be crowned by the largest dome in the world. This decision by Florentine officials and citizens was "a remarkable leap of faith" –to build a dome so large that no one at the time had any idea of how to build it, or even if it was possible to build. Yet they had faith that in time someone would come forward with a way to solve one of the greatest architectural problems of all time. (Ross King, Brunelleschi's Dome, Walker and Company, New York © 2000).

Today, NASA faces an enormous, seemingly unsolvable, technical challenge—how to safely send and return human explorers to Mars and possibly beyond. And like the citizen's of Florence, NASA and the American people have begun to push forward with what could be the greatest achievement of mankind, with faith that solutions will be found to the enormous technical and cost hurdles.

With this in mind, NASA has begun a focused effort to identify the issues and requirements for enabling successful human exploration missions. One well known issue is controlling the health risks to humans resulting from exposure to high-energy charged particles in galactic cosmic rays (GCR) and solar particle events (SPEs). Controlling the health risk from space radiation exposure requires a detailed understanding of its composition, energy spectra, climatology and weather. Such understanding is required to successfully design mission architectures, spacecraft, rovers, and mission operations which reduce/maintain astronaut's radiation exposures within established radiation safety guidelines.

The Sun-Solar System Connection (SSSC) Division seeks to understand the origin and evolution of high- energy processes in the Sun, the structure and physical processes of our star's heliosphere and Earth's magnetosphere, and the energy and mass coupling between the Sun and the Earth's magnetosphere, ionosphere, and thermosphere. Some of the SSSC's existing and planned space physics missions have the potential to directly contribute to understanding the composition, energy spectra, climatology, and weather and forecast ability of GCR and SPEs.

At the request of Dr. Richard Fisher, Deputy Director of the Earth-Sun Systems Division, and Dr. Madhulika Guhathakurta, LWS program scientist, a workshop was convened of scientists and other experts in space weather, space radiation, space physics, and solar physics. Its purpose was to identify which elements of the current and planned SSSC fleet contribute to the improved understanding of GCR and SPEs in the context of enabling human exploration missions as well as which critical areas are not being addressed by the current planned program.

CHARGE TO WORKSHOP MEMBERS

The charge presented to the workshop team by the workshop chair, Mr. Michael Golightly (NASA Johnson Space Center):

"We are asked to support the NASA Sun-Earth Connections Program by identifying areas in which the Living With a Star (LWS) program can contribute to the successful implementation of this new 'space exploration vision:'

- Develop a list of space physics/weather areas requiring further research or study in order to support the design and implementation of manned lunar and Mars missions;
- Provide this information to SEC in order to help identify how existing and future SEC missions and research can support these exploration goals."

The product anticipated from this workshop was a report to the SSSC Division identifying:

- Space physics/weather areas requiring further research or study in order to support the design and implementation of manned lunar and Mars missions;
- Areas addressed by currently designed SSSC missions; and
- Areas that are (potentially) addressed by future SSSC missions.

In addition, the report would include recommendations for ways to address outstanding areas/problems not currently addressed by the SSSC program. This report represents the planned final product.

FRAME OF REFERENCE FOR THE WORKSHOP DISCUSSIONS

Astronaut space radiation exposure during exploration-type missions, and the methods to control and reduce it, are dependent on many physical factors, including length of mission, effective shielding inside a spacecraft, the amount of time spent on the surface of a planet or moon, effective shielding inside a surface habitat, duration of surface exploration away from a radiation protected area, the effective shielding provided by the planet's or moon's atmosphere (and seasonal variability), and phase of the solar cycle.

Each of these factors has a varying degree of importance to astronaut radiation exposure depending on the type of mission. To help better understand each factor's relative importance, and therefore to establish priorities, these factors were considered in the broad context of two missions classes: (a) those involving multiple missions to the lunar surface over an extended period of time and (b) a (temporary) manned exploration of Mars. More permanent Mars surface missions were judged to be well beyond the time horizon of this analysis.

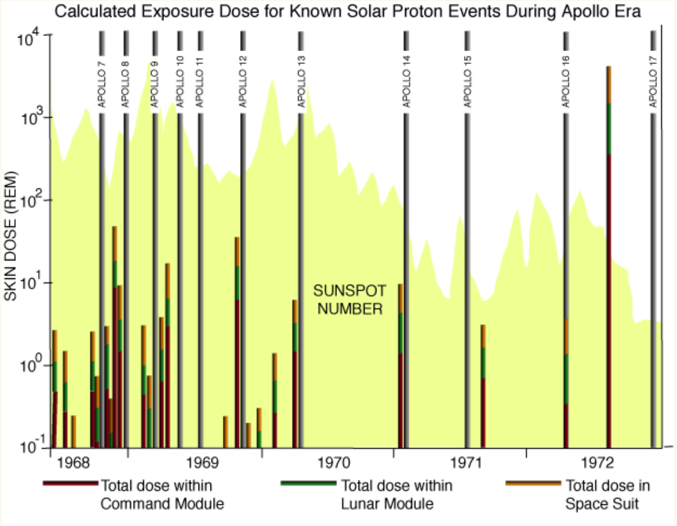
To further help focus the workshop's activities and better assess the importance of these factors, some reasonable assumptions were made regarding lunar surface and manned Mars exploration missions.

EXPLORATION-CLASS MISSIONS—STARTING ASSUMPTIONS

Lunar Surface Mission Scenario:	*Manned-Mars Exploration Mission Scenario:*
• Occurs before the Mars exploration missions;	• Occurs after lunar surface missions;
• Involves multiple missions over numerous years;	• Involves single multiyear mission;
• A shielded environment will be available on the lunar surface;	• Crew transfer vehicle will be very substantial;
• Crew will transit to and from Moon via a modest transfer vehicle	• Crew surface habitat will provide shielding;
• Transit to/from Moon requires ~3 days each way;	• Mission will occur near solar maximum;
• No crew remains in lunar orbit;	• Possible long surface excursions;
• Possible long lunar surface excursions.	• Crew will be exposed to SPEs during the mission.

These assumptions should NOT be construed in anyway as specific mission designs being planned by NASA. Rather they are simply reasonable assumptions derived from the Apollo missions as well as a number of exploration mission studies conducted over the past decade.

Using these assumptions, astronaut radiation exposure concerns can be viewed as the result of galactic cosmic rays (GCR) and large (1 in 10 years) solar particle events (SPEs). Geomagnetically trapped radiation, the trapped inner belt energetic protons and outer belt electrons, are not viewed as a major concern for astronauts. Based on the Apollo program experience, the trajectory to and from the Moon (and presumably interplanetary) trajectory rapidly transits through the trapped radiation belts, resulting in an exposure to the crew that is small compared to the expected total GCR exposure and any exposures from SPEs. The assumption of rapid transit through the trapped belts should be reexamined in the future as mission concepts and plans mature.



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.

EXPLORATION-CLASS MISSIONS—ASTRONAUT RADIATION SAFETY CONCERNS

Lunar Surface Mission Scenario:	*Manned-Mars Exploration Mission Scenario:*
• Transits through geomagnetically trapped radiation;	• GCR exposure during transit to/from Mars;
• Avoiding SPEs during transit to/from Moon;	• GCR exposure on the Martian surface, especially from the cascade of radiations ("secondaries") produced by GCR ("primaries") in the Martian atmosphere
• GCR exposure during lunar surface stay;	• Large SPEs during transit to/from Mars;
• Large SPEs during long lunar excursions away from shielded environment	• Large SPEs during long excursions away from shielded habitat.

GCR and SPEs are both areas which fit naturally within the existing SSSC program.

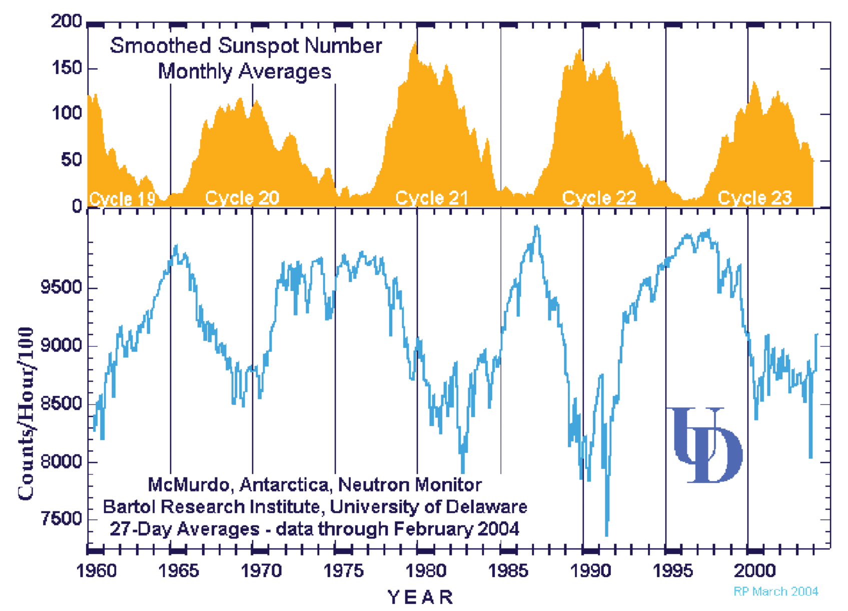
There are a host of other issues, most notably radiobiological effects and potential mitigation techniques, which play an even more important role than physical factors in determining the risk from space radiation exposure. These issues were not part of the frame of reference for this workshop. Exposures from potential nuclear power sources and the environmental impact to electronic parts and systems, surface materials, etc. are also not addressed in order to keep the scope of this report consistent with the major focus of the workshop topics. These and other risk areas are being addressed by other sectors within NASA.

STATE-OF-THE-ART: OUR UNDERSTANDING OF GCR AND SPE CLIMATOLOGY, WEATHER, MONITORING, AND FORECASTING AS RELATED TO EXPLORATION MISSIONS

Human Health Risks from Space Radiation Exposure: Although the focus of this workshop was to gain a sufficient understanding of the space radiation environment to support exploration-class missions, the ultimate goal actually is to understand and mitigate the effects of this environment on the crew and sensitive spacecraft components. In the case of the crew, epidemiological studies of human radiation exposures and radiobiological research conducted over the past six decades have uncovered a panoply of health risks associated with radiation exposure. These health risks include: cancer and cataract induction; heart, digestive, respiratory, and neurodegenerative diseases; fibrosis and vascular damage; immunological, endocrine, hereditary, and central nervous system effects; and acute effects.

Uncertainties in Quantifying Health Risks and Effects: Accurately quantifying the radiation-related risks to crews during exploration missions is fraught with large uncertainties due to the paucity of human heavy-ion radiation exposure data, errors resulting from extrapolating results of animal experiments to human exposures, and the uncertainty associated with interpolating human and animal data necessarily obtained at high exposure rates to the much lower rates that will be experienced by the crew. The uncertainty in the computed exposure and risks used for radiation health protection planning and spacecraft design has an enormous impact on the ability to even attempt an exploration-class mission. To compensate for large uncertainties, additional mass may needlessly be added to a spacecraft to ensure adequate shielding of human and critical spacecraft components. The additional mass leads to larger vehicles and/or less usable volume, resulting in significant additional costs (in terms of energy and money) to launch the spacecraft and propel it to and from the Moon or Mars, or reduced vehicle and crew capability.

GCR Flux Climatology: There are multiple temporal trends in GCR flux rate as determined from direct measurements, ground-based neutron monitor data, and cosmogenic Be-10 (ice core) and C-14 (tree ring) proxy measurements. A prominent trend in GCR flux is solar cycle modulation, with the maximum flux occurring near solar minimum and the minimum flux occurring near solar maximum. For the portion of the GCR of importance to astronaut exposures (i.e., < 2 GeV/n, a measure of a nuclei's specific kinetic energy or speed), the GCR flux varies by a factor of two to five (depending on energy) from solar maximum to solar minimum. The magnitude of the GCR flux at solar maximum remains approximately the same from one solar cycle to another (within a factor of 2). Although the flux at solar minimum during the space era has been relatively constant from solar cycle to solar cycle, there are large differences in the length of the solar minima (odd-even cycle effect). In addition, there are longer-term trends in GCR flux related to long-term changes in solar activity. For example, cosmogenic Be-10 production was thirty percent greater prior to 1900 than it is today. In choosing the magnitude of GCR flux to be used in spacecraft and mission design, the GCR flux during the 1954 solar minimum epoch is more representative of the maximum expected flux than using the GCR flux from a more recent solar cycle (which in general are more active than the known historical record), and it is possible the flux could return to pre-1900 conditions within the time span envisioned for the initial manned Mars mission(s). It is now recognized that most of the modulation of cosmic rays in the heliosphere takes place in the heliosheath, the region between the solar wind termination shock and the heliopause. As a result, continued measurements by the Voyagers in this region are the key to understanding and modeling the worst-case cosmic-ray conditions in the inner heliosphere.



Solar activity and radiation levels. The GCR flux, as represented by the ground level neutron flux (blue curve) is anti correlated with the level of solar activity represented by the smoothed sunspot number (solid yellow curve). Credit: University of Delaware/Bartol Research Institute.

GCR Gradients in the Heliosphere: Spacecraft measurements and theoretical studies have demonstrated that a positive gradient (rising) exists in GCR flux with radial distance from the Sun, with the flux increasing with increasing distance. The magnitude of the gradient is relatively small and depends on the solar magnetic polarity. Based on data sets from IMP, Voyager, and Pioneer, the magnitude of the gradient is approximately ten percent per astronomical unit at 1 AU, and four percent per astronomical unit at 5 AU. The GCR flux at Mars is expected to be two percent greater than the flux at Earth. (It should be noted that most analysis of GCR flux gradients have been done for distances of greater than 5 AU, well beyond the orbit of Earth and Mars.) The differences in particle flux between the GCR models developed for Earth's orbital distance and those encountered at Mars' orbital distance are expected to be relatively small in comparison to others in the complex web of uncertainties and errors in astronaut radiation risk assessment for exploration missions.

GCR Environment Models for Supporting Spacecraft Design: Neutron monitor, film emulsion, and charged particle measurements collected from ground-based, balloon-based, and space-based experiments over the past six decades have been melded together by various groups to produce numerical models of the GCR composition and flux at Earth. These models have been an important tool for designing spacecraft and assessing the risk to astronauts on the Space Shuttle, ISS, and future missions to Mars. The most widely used GCR design models such as the widely used Cosmic Ray Effects on Microelectronics package (CREME96, Tylka et. al., https://creme96.nrl.navy.mil) and in use at Moscow State University (Nymmik, et. al., http://www.npi.msu.su/gcrf/form.html.), as well as the independently developed NASA Johnson Space Center model (Badhwar, G.D. and P.M. O'Neill. "An Improved Model of Galactic Cosmic Radiation for Space Exploration Missions." Nucl. Tracks Radiat. Meas., 20 (3), (1992) p. 403; model available at - http://www4.jsc.nasa.gov/org/Ev/ev5/index.html or by sending an e-mail to Patrick.m.oneill@nasa.gov.), are empirical models using various schemes to account for temporal variations in GCR flux. These models, developed in the 1980s-1990s and updated over time, have greatly improved the ability of scientists and engineers to model the GCR absorbed dose, LET spectra, and SEU rates aboard Earth-orbiting spacecraft. These models, however, do not accurately reproduce all of the GCR measurements from ACE, HEAO-3, and other spaceflight and balloon experiments. Scientists at JPL and Caltech have recently produced a physics-based model that demonstrates improved accuracy when compared to ACE measurements (Davis, et. al. "Solar Minimum Spectra of Galactic Cosmic Rays and Their Implications for Models of the Near-Earth Radiation Environment." JGR, 106(A12), (01 Dec 2001) pp. 29979-87). The model is based on underlying astrophysical processes that determine the composition and energy spectra of the "local interstellar spectra" and the effects of transport in the heliosphere. Given the expected importance of GCR to crew exposures during exploration missions, further work can and should be done to understand this important radiation source. Research areas to be pursued include: continued measurements of the variation in GCR fluence rate in response to solar and heliospheric variations; understanding and modeling the solar activity-induced modulation of all GCR species and energies using models that extend from the Earth to the heliopause; improve physics-based and semi-empirical models of GCR composition and energy spectra; and investigate long-term trends, beyond the past few solar cycles, in GCR fluence rates.

SPE Gradients in the Heliosphere: In previous studies that examined SPE particle measurements from multiple spacecraft at varying distances from the Sun, the gradient in peak intensity was found to be about R-3, and the total fluence gradient as R-2 (R being the distance from the Sun expressed in AU). However, the interpretation of these measurements is currently a subject of some controversy, and there is a need for additional SPE measurements by spacecraft at different radial distances from the Sun.

SPE Composition: Most studies examining the health risk from SPEs to humans during spaceflight focus on the proton component of the events. In all SPEs, protons are the dominating component of the total charged particle fluence. In most events, heavy ions contribute only a small fraction to the total event particle fluence. In comparison with nominal quiescent background rates, however, the fluence rate during SPEs of heavy ions such as C, O, and N with energies up to 150 MeV/n can increase by a factor of one hundred. Above 150 MeV/n the GCR heavy ion component dominates the fluence rate (although during the January 28-29, 2001 event heavy ions possibly were measured with energies of up to 2 GeV/n). During some SPEs the intensity of ions heavier than Fe increase by up to a factor of a thousand over background levels, although these tend to be during small events and at low energies. The typical levels of shielding mass in manned spacecraft effectively protect crews from these SPE heavy ions; these ions can be a more significant risk, however, for thinly shielded electronic components on the outside of spacecraft or humans in thin spacesuits working outside of shelter on the surface of the Moon. Further research is needed to understand the range and cause of the event-to-event variation in the abundance and energy spectra of SPE heavy ions.

SPE Fluence Models for Supporting Spacecraft Design: Critical to the ability to design human exploration spacecraft and plan exploration missions is the ability to accurately specify cumulative SPE fluence and worst-case SPEs as functions of mission duration and user confidence level. Engineers will require specifications of the upper bounds of cumulative SPE particle fluence for an entire mission, and the total fluence and peak fluence rate from a worst-case event during a mission. Work done at the Naval Research Laboratory and NASA Goddard Space Flight Center has resulted in the new design model "Emission of Solar Protons" (ESP, http://see.msfc.nasa.gov/ire/model_esp.htm or http://trs.nis.nasa.gov/archive/00000505/01/tp209763.pdf). The model computes the probability of a cumulative SPE fluence and/or worst-case SPE fluence at 1 AU as a function of mission duration and confidence interval. The model was developed from proton measurements made by the IMP3-8 and the GOES 5-7 series of spacecraft. The majority of the data used in the model are measurements from the IMP-8 spacecraft's Goddard Medium Energy instrument (30 energy bins covering the range 0.88 to 485 MeV). The IMP-8 dataset provides nearly continuous coverage since 1973 (albeit at a duty cycle of ~50%). Periods with data gaps or exhibiting detector saturation were supplemented by measurements from the SEM instrument on the GOES 5-7 spacecraft series. Maximum entropy theory was used to find the best fit probability distribution function for the number of SPEs per year with a cumulative integral fluence in excess of some value. A truncated power law function resulted in the best fit. Using this distribution in conjunction with extreme value theory, probability distributions were derived for "worst case" (i.e., cumulative integral fluence above some particle energy from a single event) as a function of confidence level and mission duration (years). This analysis resulted in an upper bound ("design limit") for a single "worst case" event of 1.32x1010/cm2 for the integral fluence of protons with energies greater than 30 MeV. From these results, the probability of exceeding a cumulative fluence as a function of mission duration and particle energy was found, as well as integral proton energy spectra as a function of mission duration and confidence levels. The statistical portion of the model is valid for energies from greater than 1 to greater than 100 MeV. There are insufficient data, however, to directly extend the model to the higher particle energies of prime importance to crew exposures inside a spacecraft. Due to this lack of data, the higher energy portions of the SPE spectra are scaled from the lower energy portions, resulting in a source of uncertainty in determining the amount of shielding necessary to protect crews from SPEs during multi-year missions. The ESP model provides a statistically rigorous tool that can be used by exploration spacecraft and mission designers to determine SPE shielding requirements for the crew and electronics and other sensitive devices. Improving and expanding the model by incorporating SPE heavy-ion data will further benefit spacecraft designers.

SPE Impact and Mitigation: Calculations show that for an astronaut in an EVA suit (e.g., working outside a shelter on the surface of the Moon), currently established astronaut radiation exposure limits (30-day limit) will be exceeded in the case of the blood forming organs (BFO) by an SPE fluence of 5x108/cm2 protons with a critical energy of approximately 70 MeV, and in the case of the skin a fluence of 2x108/cm2 protons with a critical energy of 20 MeV. Using a DoD model of survivability from acute exposure to ionizing radiation, this same astronaut would have a 1% chance of near-term mortality if exposed to an SPE such as the 4-7 Aug 1972 event, a 12% chance of mortality after exposure to an event twice as large as the Aug 1972 event, and an 87% chance of death following exposure to an event four times larger. The 4-7 Aug 1972 SPE is frequently used as a worst-case event standard because it is the largest for which we have direct particle measurements. The SPE which occurred in Feb 1956, inferred from ground-based and balloon-borne measurements, produced the largest ground level event (GLE)—a large increase in the background ionizing radiation intensity or neutron fluence rate—since measurements began in the mid-1940s. GLEs are indicators of very energetic SPE protons-- at least 1 GeV--and hence large, powerful events. These very high-energy protons are of greatest importance to crew exposures inside the anticipated relatively thickly-shielded manned spacecraft, surface habitats, or “storm shelters.” The intensity of high-energy protons in the Feb 1956 event was thirty to four hundred times as great as in the 4-7 Aug 1972 SPE. Using an event with a fluence four times larger than the Sep 1989 SPE as a design criteria (a more modern event which also produced very high energy protons), a spacecraft or surface shelter that keeps astronaut exposures below the allowed exposure limits will also preclude astronauts from suffering any significant acute medical effects from exposure to an event like the one that occurred in Feb 1956.

Direct exposure from incident SPE particles is not the only source of exposure—thick materials, such as the lunar or Mars surface, exposed to SPE protons produce secondary neutrons which backscatter through the material surface. The composition of the thick material has a major impact on the amount of backscattered neutrons. For example, ten times more backscattered neutrons with an energy of 10 MeV are produced from lunar regolith than from a thick volume of water (e.g., a water tank.); the backscatter flux produced from a thick layer of carbon dioxide (e.g., Martian atmosphere during Martian summer) is in between that of water and regolith. Secondary neutrons are also produced through nuclear interactions of SPE protons as they pass through structural materials, such as those used for an astronaut habitat or shelter. A critical factor which must be considered in determining the amount of shielding necessary to protect crews from SPE exposures is whether or not crew members will take part in multiple exploration missions. Crews who participate in more than one mission will require greater levels of shielding in order to ensure that they do not exceed established maximum cumulative exposures during multiple missions.

Space Climatology and Space Weather Requirements to Support Radiation Health and Safety: Since the inception of manned spaceflight, scientists and engineers concerned with protecting crews from excessive radiation exposure have struggled to answer seemingly simple questions: what is the biggest SPE that can occur, and how likely is it to occur during the mission? What is the appropriate engineering design criteria for protection from SPEs? What is the probability of exceeding the engineering design criteria? What is the risk of exceeding the design criteria? Although much progress has been made (e.g., see discussion of ESP model above), definitive answers to these questions do not exist. From a radiation health perspective, answers to these questions are the highest priority space weather needs for planning long-duration human missions away from the protection provided by the Earth's inner magnetosphere. Making accurate radiation protection risk-based decisions with high confidence requires: a statistics-based model of differential proton energy spectra for large SPEs; a statistics-based model of the rate of increase in proton fluence rate (from event initiation to peak rate); a statistics-based model of peak SPE fluence rates; and the ability to forecast periods of no SPE occurrence with a greater than 99% accuracy.

Space Weather (SPE) Forecasting: A dramatic improvement in SPE monitoring has occurred over the past twenty years. For example, for missions in the vicinity of Earth, such as lunar missions and those in LEO, changes in the low-energy proton flux upstream of Earth (i.e., at the ACE spacecraft) can be used as an indication that an interplanetary shock driving a SPE is propagating towards Earth. However, the accuracy of one to three day forecasts of SPE occurrence are not much different today from those made twenty years ago. While the monitoring of SPEs has significantly improved, SPE forecast accuracy has not yet reaped the benefits. When an event occurs at the Sun, mission flight controllers will require space weather forecasters to provide answers to: will this event generate a SPE? When will the SPE start? What will be the maximum fluence rate? When will it reach maximum intensity? How long will the event last? Accurate and reliable answers to these questions require improved space weather forecasting models.

Progress has been made toward modeling CME propagation from the Sun through the heliosphere using MHD codes such as "BATS-R-US." Using only a solar magnetogram and CME eruption time, BATS-R-US can model the evolution of a CME's location and structure, including the associated upstream shock, from the Sun to beyond Earth. The BATS-R-US model uses a "seed population" of 5 keV protons and produces high-energy particles accelerated near the Sun. In a recent test of the system, BATS-R-US was used to simulate the 2 May 1998 CME and subsequent SPE. For this event the model produced a peak proton event intensity at the location of Earth 4 hours after the onset of CME eruption. Comparison of the model results to GOES-8 measurements showed good agreement for six of the available integral energy channels (>5, >10, >30, >50, >60, and >100 MeV), with slightly worse agreement with the >1 MeV channel. A system capable of modeling CME evolution could allow space weather forecasters to predict the impact of a CME and shock accelerated particles to an exploration spacecraft, even if it we not in the vicinity of Earth. The BATS-R-US software still requires considerable development effort before it could be used as an operational space weather forecasting tool.

In addition to predicting the evolution of the CME itself, progress has also been made over the past decade towards predicting the total exposure (impact) to an astronaut from an event based on the event's early evolution. The cumulative absorbed dose from an event is well modeled by a Weibull distribution of the form $D(t) = D\infty(1-\exp(-t/\beta)\alpha)$, where t is time from event onset and $D\infty$ is the final astronaut absorbed dose. Using the measured cumulative absorbed dose at several points early in an event, a trained time-delay neural network can predict the best fit values for the Weibull parameters, including the final astronaut absorbed dose.

One basic result that has emerged from this study is that all "big" events, those that produced high final absorbed doses, all had high initial dose rates—there were no cases of big events which had low initial dose rates. For the 4-7 Aug 1972 SPE, the best fit final dose was obtained seven hours into the event. For the Oct 1989 sequence of SPEs, the best fit total dose from the first event was found nine hours into the event, and six hours after onset in the case of the second event. In an analysis of a large group of historic SPEs, the majority of forecast total absorbed doses are within 10-20% error of the actual final value before half of the event dose was received. However, sometimes one parameter was not adequately forecasted, which causes the event to be either over or under-predicted..

A manned exploration mission to Mars also raises a problem not previously encountered in providing operational space support—the crew and spacecraft can be exposed to a side of the Sun out of view to ground-based space weather forecasters. The only way to avoid missing potentially harmful SPEs is to provide complete monitoring coverage around the Sun with space-based observatories and sensors.

IDENTIFIED RESEARCH NEEDS

Following the planned talks, workshop members broke into four groups to identify space weather and climatology issues related to the successful execution of manned exploration missions. Three groups examined the GCR, SPE, and surface radiation environment information and models that engineers will need in the future to incorporate adequate radiation shielding for crews. The fourth group examined potential space weather impacts to mission operations and the capabilities, tools, and data that will be necessary for mission support.

The issues and recommendations identified by the workshop members are consolidated below into six groups: SPEs, GCR, in-situ measurements, infrastructure needs to support in-situ measurements, SSSC spacecraft, and miscellaneous. No attempt is made at prioritizing these recommendations; the listed recommendations only identify areas where SSSC's program can support and enable the proposed exploration initiative. The relative importance of each recommendation should be evaluated before dedicating resources towards their implementation. The workshop panel's general consensus is that the greatest contribution SSSC can make towards supporting and enabling exploration missions will come from implementing the SPE-related recommendations.

Solar Particle Events (SPEs)

SPEs were first detected during the 1940s by ground-based ionization monitors and then through the recognition that geomagnetic polar cap absorption events were the result of precipitation of ions of tens of MeV from the Sun. Measurements on spacecraft beginning in the 1960s have determined the spectra, composition, and temporal and spatial variations of SPEs with increasing precision and accuracy. The strong association of SPEs with large solar flares led to the view that all the energetic particles were accelerated in flares themselves and somehow escaped from the solar corona, generally after significant coronal propagation. The predominant view today is that most solar energetic particles observed at 1 AU are produced in coronal and interplanetary shocks driven by CMEs. The focus on the solar origin of SPEs has shifted from flares to CMEs, and it is now believed that fast and wide CMEs are prime candidates for SPEs. However, it is still not possible to forecast with accuracy whether a particular observed CME will result in an SPE at Earth, and if so, the intensity or duration of the event. The peak intensity of SPEs, in particular, can vary over orders of magnitude even when associated with apparently similar CMEs. Energetic particles are observed at some interplanetary shocks that pass the Earth, but these are generally limited to several tens of MeV in energy, one to two orders of magnitude below the energies of the most damaging SPEs. Further, the problem exists that while some correlation of SPE energies and/or intensities is found with shock speeds, most interplanetary shocks produce no observed particles in the MeV range. The processes by which shocks begin to accelerate particles are therefore not understood on an observational or theoretical basis.

To support the goals of the exploration vision, SPEs must first be well characterized in terms of their observed spatial, temporal, size, spectral, and compositional properties. Then the significant physical factors that lead from solar eruptions to the production of SPEs must be determined and modeled and validated before there can exist a predictive capability of real value to enabling exploration missions.

We need to understand how SPE peak intensities and fluences vary with both radial distance from the Sun and azimuthally from the nose of CME-driven shocks. Recent shock modeling and observations have suggested streaming upper limits with an R-3 dependence for intensities of large SPEs observed well away from the shock sources. Those limits appear to be reasonably well established at low ($E < 30$ MeV) energies, but they are not observationally confirmed at the higher SPE energies of importance for human exposures, and no limits have been established for SPE intensities in the vicinities of shocks. The azimuthal spatial variations of SPEs are not well known other than being strongest along magnetic field lines connecting to near the nose of the shock; there appears to be a decrease in intensity of approximately an order of magnitude for every radian of separation from the nose. The azimuthal intensity variations from SPE to SPE are uncharacterized and may be considerable. A further complication is that the spatial variations may be very time dependent. The phenomenon of "invariant spectra" begins near shock passage and results in very homogeneous spatial distributions both in solar radius and azimuth behind the shocks. Observations by spacecraft distributed in heliospheric longitude and distance from the sun are needed to characterize these phenomena more accurately.

The occurrence of SPEs on yearly time scales roughly follows the solar activity cycle, although significant SPEs can occur at any time, particularly during the decline to solar minimum. The JPL model of SPEs is based on space observations over the last four solar cycles, and gives probabilities of daily average particle intensities at all levels for a range of proton energies up to E > 95 MeV. The model is roughly divided into a 4-year period of low SPE probabilities around solar minimum and high probabilities for a 7-year period around solar maximum.

Timescales of the SPEs themselves are not well characterized. More progress is necessary in predicting the onset, rise, peak, and fluence decay times at any point in space for a given solar eruptive event. These parameters, used in current 1-AU prediction models, are only roughly characterized with averages based on associated solar flare locations for SPEs observed with older data sets such as that of IMP-8. How the various SPE time scales for solar events differ at a given location is not known. The dependence of SPE time scales on particle intensity is also not known.

An accurate assessment of the probabilities of occurrence of extremely large SPEs are critical for the design and preparation of an exploration mission. The distributions of peak intensities of SPEs have been compiled by many investigators using SPE data from the space era. The relative frequency of SPE occurrence as a function of the peak intensity at any particle energy generally follows a power law, as is observed for many natural phenomena. However, at the high intensity end of the distribution the numbers of observed events are few and the occurrence probability of extreme SPEs lies in uncharted territory. There is insufficient understanding of the physics of CME-driven shocks to determine the upper limits of SPEs in the heliosphere. We can expect some natural constraint on SPE size based on shock size and speed and magnetic field strengths and abundance of seed particles, but these limits are not well known.

The results from the space-era SPEs can be supplemented by the recent work involving SPE fluence records in nitrate concentrations from polar ice cores. These ice core studies have recently produced statistics of large SPE fluence at E > 30 MeV dating back to 1561. In these ice cores the famous event of 1 September 1859 appears to be the SPE with the largest fluence since 1855. These historical events are not yet the basis for model predictions.

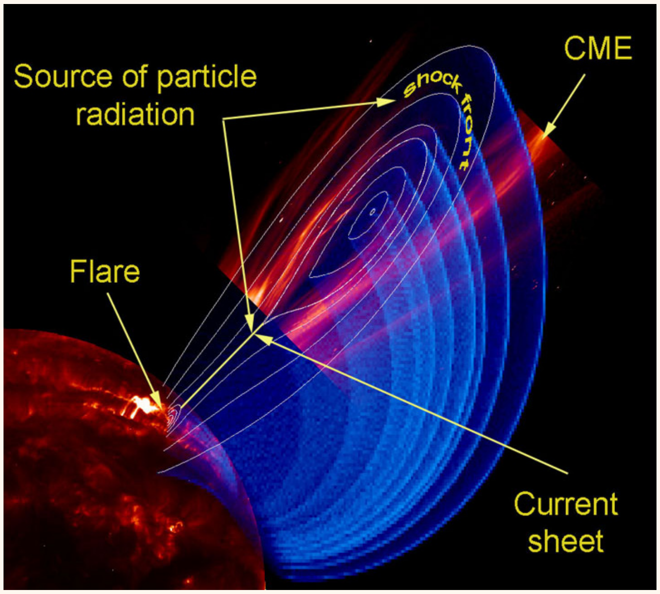
The spectra of SPEs are generally consistent with the power laws in energy expected from shock acceleration. The observed spectra at any point are continuously changing due to velocity dispersions early in events, and later to the energy dependence of the particle scattering processes and changing shock locations. However, it is also recognized that a bend (“knee”) usually occurs in SPE spectra. The slope of the spectra beyond the “knee” is typically steeper, resulting in a greater rate of decrease in intensity with increasing particle energy. This has important implications for the VSE. An event with a “knee” at a low-energy may be very intense at low energies but very weak at high energies. On the other hand, if the “knee” lies at high energies, then the event may be intense throughout the energy range of concern. Energy spectra have been statistically compiled at several tens of MeV from older space data sets, but their application or extension to higher energies for any given SPE is doubtful when the knee energy remains unknown. This ignorance is due largely to the lack of observations at the higher (30 to 300 MeV) energies where knees occur. Particle anisotropies may also complicate the observations. It is important to determine the “knee” energies of heavy ions (Z > 2) to determine their dependence on Q/M (ion charge-to-mass ratio) values.

Two broad categories of events have been uncovered from observations of many SPEs. Impulsive SPEs are marked by enhanced abundances of high-Z ions, high charge states, and relatively low particle intensities. Gradual SPEs are the larger events and characterized by abundances and charge states similar to those of the solar corona, at least for low energy ions (at higher energies-- > 30 MeV/n—heavy ion composition becomes more variable). Gradual SPEs are the greater concern for exploration missions. Over the last decade new measurements extending to much lower particle energies (< 1 MeV/n) and measurements of particle charge states as a function of energy have shown new complexities in the simple two-class SPE picture. Some gradual SPEs have shown ionic compositions resembling the high-Z-rich impulsive SPEs and in many cases the ionic charge states have increased with energy. These results have cast into doubt the former view of gradual SPEs as resulting only from the shock acceleration of ambient coronal or solar wind thermal particles. Previously accelerated particles, nonthemal ion tails, and pick-up ions of various sorts are now considered to be candidate seed particle populations.

Continued observation and characterization of the SPE ionic and charge state composition are important for two reasons. Heavy ions, a concern for astronaut radiation safety due to their high LET, are sometimes significantly enhanced over coronal abundances, with the enhancements increasing with Z. Compositional variations also provide insight into the nature of the intertwined problem of the shock (or other) acceleration process and the seed population.

There is a wide gap between what models, (with their requirements for ad hoc inputs) predict and the reality of shock acceleration. Several shock models are under development to calculate the spectral and temporal variations of SPEs. These models need as inputs the seed population characteristics as well as the shock and ambient solar wind characteristics. Those inputs can be obtained with in-situ observations of shocks at 1 AU, but at those times the shocks are considerably weaker than when they were near the Sun and accelerating particles to much higher energies. Therefore, to improving these shock models it is critical to determine the various shock input parameters as close to the Sun as possible (plasma density, beta, magnetic fields and their fluctuations, and seed particles); these measurements will provide realistic inputs into the models for validation purposes. Studies over the past decade have shown that most interplanetary shocks do not appear to accelerate particles to high (MeV) energies, and even simple rules for which shock parameters are necessary for acceleration are not clear.

Improving model reliability will therefore require improving the currently poor understanding of shock formation by CMEs. The CME structure and development is crucial to determine the subsequent formation of shocks and production of SPEs. Specifying only the CME leading edge speed profiles and widths in the plane of the sky is simply inadequate to determine the complexities of driven shocks. Recent work has involved using spectroscopic and polaroid techniques to unravel the CME 3-dimensional structure, and stereoscopic techniques are being developed to take advantage of future STEREO coronagraph observations.



One of the most difficult problems in space weather is the prediction of Solar Energetic Particles. These relatively rare events travel from the Sun to Earth in about an hour, giving astronauts and spacecraft operators little time to prepare. New theoretical models are providing information about the precise source region of the energetic particles. Instead of blasting outward from the flare itself, it is proposed that many of these particles arise in a thin electrified sheet of gas that stretches from the flare site to the base of the coronal mass ejection. This current sheet acts much as an particle accelerator, pushing atomic particles to almost the speed of light. Credit: SAO and SOHO (ESA/NASA)

Specific Solar Particle Event (SPE)-Related Requirements

- Characterize peak intensities and total fluence as a function of solar distance.
  - Obtain new, multipoint charged particle measurements within the inner heliosphere to sample radial and azimuthal flux variations
  - Continue studies with existing data sets from older missions (e.g., Helios, ISEE-3, Voyager) to determine better the spatial variations.

- Obtain better understandings of SPE phenomenology on multiple time scales to improve probabilistic occurrence models and short-term forecasting following event initiation.
  - Use currently available data sets to characterize SPEs time scales at various energies relative to CME parameters and locations.
  - Examine historic data (e.g., ice cores) to extend knowledge of the time variations of large SPEs occurrence rates.
  - Update intensity and fluence models with more recent observations, including heavy ions.

- Determine the magnitude and frequency of credible extreme events for use by spacecraft and mission designers.
  - Continue analysis of extreme SPEs using any historical records that reflect the fluence of SPEs.
  - Confirm the validity of the theoretical streaming limits with observations at different solar radial distances and higher particle energies.

- Quantify the spectral shape variability within and between SPEs.
  - Develop instruments to extend the observing range to E > 500 MeV/n to determine how the energies of the spectral knees vary among SPEs and with Q/M within SPEs.
  - Look for shock observational or modeling characteristics that may determine the knee energies of SPEs.

- Quantify the composition variability between SPEs.
  - Develop instrumentation to extend elemental charge states to higher (E > 1 MeV/n) energies and to resolve high-Z elements at and above Fe (Z = 26).
  - Continue analyses to characterize the compositional and charge state variations as functions of energy among SPEs.
  - Continue analyses of SPE characteristics to determine acceleration process(es) and seed particles.

- Develop physics-based models of SPE acceleration and spatial evolution.
  - Make the in-situ inner heliosphere measurements necessary to improve shock models.
  - Continue development of shock models with attempts at validation whenever possible.
  - Make stereo, spectroscopic, and polarized observations of CMEs to determine their structures and shock development.

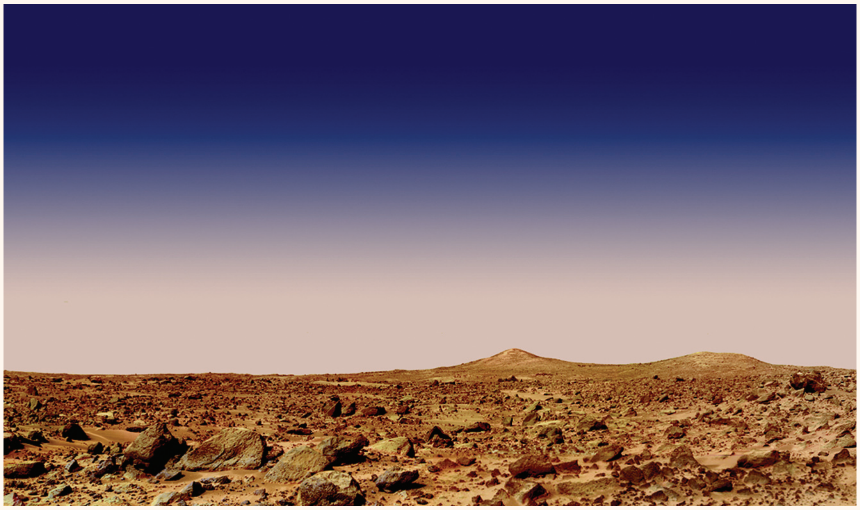
Galactic Cosmic Rays (GCR)

A subgroup of the workshop participants outlined requirements for improved modeling of the GCR radiation environment and for accurate measurements of cosmic rays over the solar cycle in order to support the development and validation of such a model. An important aspect of such a model is accurate representation of the temporal and spatial variations of cosmic rays within the heliosphere, and recognition that it is not unlikely that the interplanetary radiation environment in the coming years will reach levels outside the boundaries of our experience during the space era.

GCR Environmental Modeling: As humans begin to journey beyond the protective cover of Earth's magnetosphere for extended periods of time, it is important to have a complete and accurate GCR environmental model available to aid spacecraft and mission design. A complete model needs to be able to reproduce the composition and energy spectra of cosmic rays from ~10 MeV/n to ~10 GeV/n, including the individual elements and abundant isotopes from H to Ni ($1 \leq Z \leq 28$). Although elements with $Z>30$ make a negligible contribution to the radiation dose, their abundance is of interest because they can produce the maximum LET that electronic circuitry can experience.

A complete GCR environmental model needs to include a physics-based model of the solar-cycle modulation of cosmic rays in the heliosphere. This needs to take into account that cosmic-ray spatial and temporal variations depend on the charge-to-mass ratio (Q/M) of the element. It must also take into account the difference in the energy spectra of the various elements that arise as a result of cosmic-ray transport through the interstellar medium. This model should have the goal of reproducing the solar-cycle variations of all GCR species over the solar cycle to within 10% at any given energy, and it should also reproduce the radial gradients in cosmic-ray intensity within the heliosphere.

It is not generally known that the space era has taken place within a relatively benign cosmic-ray environment, because the Sun has been relatively active over the past fifty years. In order for a GCR environmental model to accurately represent long-term trends in the cosmic-ray intensity, including conditions beyond those experienced over periods when spacecraft and balloon measurements of GCRs became available, it is important to link the GCR environmental model to archival records of the cosmic-ray intensity such as the Be-10 and C-14 records, and to the long-term sun-spot record of solar activity. These records reveal that Be-10 pro-



A view of the Martian landscape as may be seen through the visor of an astronaut walking on Mars' surface within the next 30 years. Mars itself will dramatically affect the radiation environment experienced by humans on the Martian surface. The Martian atmosphere provides negligible to moderate amounts of shielding from SPE and GCR particles, depending on altitude and season (lowest shielding in winter, greatest in summer). While effectively shielding out some particles, Mar's atmosphere will greatly increase the intensity of other particles (e.g., neutrons) at the surface due to the cascade formed as heavy GCR and atmospheric nuclei are fragmented during high-energy collisions. The Martian surface itself is also a source of radiation. Neutrons, formed from the interaction of nuclei in the Martian regolith with the constant shower of energetic charged particles passing through the Martian atmosphere, "back-scatter" out through the surface. Neutrons created in the Martian atmosphere and regolith may contribute a significant fraction of the exposure received by astronauts.

duction by cosmic rays was ~30% greater during the 1954 solar minimum than it was during the 1965 and 1976 solar minima, and that during 1890 it was more than 50% greater. The extreme rate of Be-10 production in recent history, about a factor of two greater than today, occurred in ~1700, near the end of the Maunder Minimum. Long-term records of Be-10 and other archives show that solar activity varies on ~200 year cycle. As a result, it is reasonable to expect the cosmic-ray intensity to begin to increase during the 21st century - the question is when, and by how much?

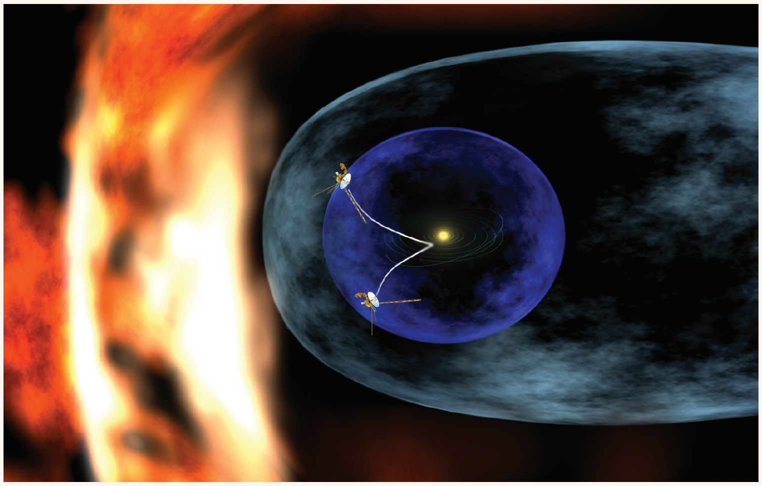
To accurately estimate the worst-case cosmic-ray intensity levels that can occur at Earth or Mars requires modeling archival Be-10 and C-14 records coupled with knowledge of cosmic-ray spectra outside the heliosphere. The spectra of cosmic rays in nearby interstellar space provide the boundary conditions that govern the solar-cycle modulation of comic rays within the heliosphere. The two Voyager spacecraft presently offer our only opportunity to directly sample cosmic-ray conditions near the heliopause where these boundary conditions can be determined.

During the past decade the statistical accuracy of both cosmic-ray and solar particle measurements in space has increased dramatically as a result of improvements in instrumentation. The ACE spacecraft is now providing measurements of all heavy nuclei with $3 \leq Z \leq 28$ over the solar cycle with more than 10 times the statistical precision and temporal resolution of previous studies. It is essential that these measurements continue to record these variations over as much of a 22-year solar cycle as possible. The best measurements of low-energy cosmic-ray H and He spectra are provided by Ulysses, IMP-8, and Voyager, with the balloon-borne experiments providing approximately once-a-year measurements of the high-energy spectra from ~0.2 to 10 GeV/n. Ground-based neutron monitors provide a long-term record that makes it possible to link the present-day measurements to earlier cosmic-ray data. These space and ground-based experiments are providing the data that GCR environmental models need to continue to assimilate, and it is essential that such measurements be continued until or unless they are taken over by next generation instruments.

In order for a cosmic-ray environmental model to predict radiation dose levels in environments that include interplanetary spacecraft and the surfaces of the Moon and Mars, it must be coupled with accurate shielding models that take into account the cosmic ray interactions and the production of secondary species that include neutrons. Although these models are developed and maintained by NASA outside of the LWS and Sun-Earth-Solar System community, they are best tested by the kinds of radiation-measuring instruments that have been developed by the space physics community. Therefore, end-to-end validation of radiation dose models requires accurate measurements of the cosmic-ray and solar-particle input to the lunar surface and to the Mars atmosphere, coupled with simultaneous monitoring of radiation levels due to charged particles and neutrons on the Lunar and Martian surfaces.

Specific Galactic Cosmic Ray (GCR)-Related Requirements

- Produce robust, state-of-the-art GCR environment engineering models for spacecraft and mission designers.
  - The model(s) must provide particle species composition (including isotopes) over the atomic number range $1 \leq Z \leq 28$ and an associated energy range of 10 MeV/n to 10 GeV/n. In addition, the model should provide an integral measure of charged particles and energy spectra with an atomic number $Z > 30$.
  - The model(s) requires a physics rather than empirical basis in order to:
    - Model particle flux climatology over various time scales including a complete solar magnetic cycle (approximately 22 years);
    - Estimate long-term trends over the next several solar cycles (derived using paleo-cosmogenic isotope records);
    - Correctly represent the particle flux gradient in the heliosphere over distances of 1-5 AU;
    - Assimilate on-going measurements of solar activity variations, such as CMEs, GMIRs, current sheet tilt, and solar B-field strength to predict GCR intensities 1-2 years into the future.
  - The model(s) must determine the flux of any particle species at any energy and any point in time, within the model's specified ranges, with an error of not more than 10%.
  - Before being released for use in making spacecraft and/or mission design decisions, the model must undergo an end-to-end validation and error assessment using GCR particle measurements made in interplanetary space (e.g., at the L1 point), above the lunar surface, and on the Mars' surface.
  - In addition to predictions of solar maximum and minimum conditions from a GCR environment model, a credible description of a "worst case" GCR spectrum (e.g., one that might have been experienced during the Maunder minimum) must be available to support spacecraft and mission designer trade studies.
  - Developing a GCR environment engineering model with the features described above requires continued synoptic measurements:
    - Ions with an atomic number $Z > 2$ by ACE;
    - Proton and helium ion measurements from Ulysses, IMP-8, and/or SAMPEX;
    - Ion measurements near the heliosheath by Voyager;
    - Measurements of proton and helium ion spectra to very high energy using balloon-based experiments;
    - Continuing the historical database of GCR flux modulation measurements by ground-based neutron monitors.



Voyager spacecraft approaching the heliopause, the boundary marking the surface of the volume of local space controlled by the Sun's expanded atmosphere—the "edge of our Solar System." The cosmic rays in nearby interstellar space is the unadulterated form of galactic cosmic rays that eventually reach the inner portions of the heliosphere (solar system) and exposure spacecraft and astronauts in transit to and at the Moon and or Mars. This "local interstellar spectra" (LIS) is then modulated in the heliosheath, the region just beyond the heliopause. The LIS and heliosheath provide the boundary conditions that govern the solar-cycle induced variations in cosmic ray intensity at the Moon and Mars. A better understanding of these boundary conditions is critical to improved modeling of long-term GCR intensity variations throughout the solar system--the two Voyager spacecraft presently offer our only opportunity to directly sample these boundary conditions near the heliopause. Other than those being made by Voyager, direct measurements near the heliopause will not be available within even the furthest time horizons of the Vision for Space Exploration, and will unlikely be available within the lifetime of anyone reading this report!

Specific In-Situ Measurement Requirements

Make detailed radiation environment measurements on Mars' surface to fill existing knowledge gaps, provide definitive environment definitions for spacecraft and mission designers, and to provide canonical datasets for end-to-end tests/validation of improved GCR environment models and heavy-ion radiation transport codes.

- Human health risk assessment and mitigations will rely critically on measurements of:
  - The differential energy spectra of protons from 10 to 1000 MeV for intensities ranging from that of the low GCR background (~3×10-1/cm2-s-ster) to those experienced at the peak of intense SPEs (to 3.5×104/ cm2-s-ster);
  - The differential energy spectra of helium ions from 100 to 500 MeV/n;
  - The LET (in tissue) spectra over a range of 100 to 30000 MeV•g/cm^2;
  - SPE intensity measurements with a temporal resolution on the order of 1-hour.

- Secondary neutrons created from nuclear interactions of GCR charged particles with atoms in the Martian atmosphere and surface material are expected to be a major source of radiation risk for humans living on and exploring the surface of Mars. This ambient neutron environment must be characterized through measurement of:
  - The thermal and epithermal neutron flux and directionality;
  - The differential energy spectra and directionality for neutrons with energies of 1 to 100 MeV (20% resolution in energy);
  - Intensity measurements with a temporal resolution on the order of 1-hour.

- The surface radiation monitoring program design should provide for continuous measurements over a period of at least 10 years in order to understand the environment's variation with cyclic solar activity.

- The varying composition and elevation of Mars' surface will directly impact the intensity and relative contributions of primary and secondary radiations on the surface. Surface radiation environment monitoring will therefore be required at multiple locations encompassing the expected range of human landing sites.

Requirements for continuous measurement of the radiation environment in Mars orbit are restricted to:
- The differential energy spectra of protons from 10 to 1000 MeV at the high fluence rates expected during intense SPEs;
- Spectral temporal resolution need be no less than 5 minutes.

Infrastructure Needs to Support In-Situ Measurements

Among the goals of the previously discussed state-of-the-art environment models is the capability to quantitatively describe the current state and future evolution of the inner heliosphere and its charged particle environment, analogous to terrestrial global weather models and forecasts.

Although there are many GCR and SPE measurements, there are relatively few made simultaneously with the same instrument at multiple locations in the heliosphere. Simultaneous measurements from L1, lunar and Mars orbits, and closer to the Sun, at a minimum, supplemented by data from other heliospheric locations, are required to provide the conditions necessary to develop, validate, and drive models of the solar wind and energetic particle environment.

Providing the necessary in-situ data and measurements to develop these proposed models (as well as providing adequate data to support future mission planning) requires a coherent infrastructure of common instruments deployed at multiple points in the heliosphere. This infrastructure needs to be developed and put into place in the near-to-mid term. Developing and deploying a coherent set of instruments can be viewed as analogous to deploying remote weather stations and new weather satellites to support the exploration and development of remote corners of the Earth.

The finite lifetime of space-based monitors and the long-term nature of the plans called for under the "vision" mandates that this be an essentially permanent infrastructure investment. NASA will need to plan for procurement of adequate numbers of instruments and provide the launch assets necessary to sustain such an infrastructure for the next twenty-five to thirty years. With the exception of stereo coronagraphs, LET measurements on the Martian surface, and neutron spectrometers on the surface of the Moon and Mars, the instruments needed for these in-situ measurements have been used on numerous space missions around Earth and throughout the heliosphere.

Specific Infrastructure Needs to Support In-Situ Measurements

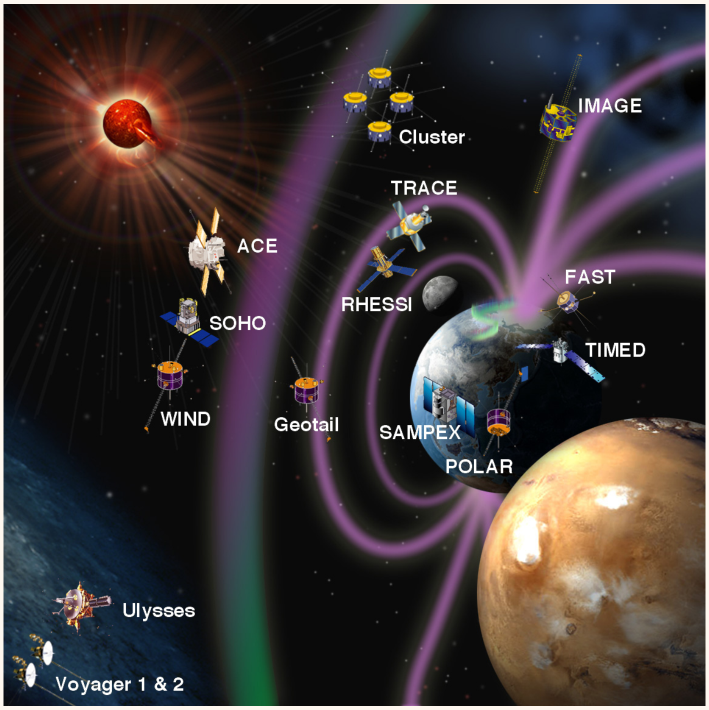
The required radiation environment monitoring infrastructure needs to consist of a common set of charged particle, LET, and neutron spectrometers deployed at multiple locations in the inner heliosphere. In the context used here, "common" means multiple copies of the same instrument, all providing the same type of data and all calibrated in the same fashion. The objective of this portion of the in-situ measurement infrastructure is to provide continuous, long-term synoptic measurements at multiple important locations in the inner heliosphere.

- A monitoring infrastructure on Mars' surface should include spectrometers to measure the:
    - Energy spectra of protons from SPEs and GCR;
    - Charge and energy spectra of GCR light and heavy ions;
    - Neutron energy spectra; and
    - Combined LET (tissue) spectra from charged particles and neutrons.
- A monitoring infrastructure at the Moon should include spectrometers to measure the:
    - Energy spectra of protons from SPEs and GCR from lunar orbit;
    - Charge and energy spectra of GCR light and heavy ions from lunar orbit; and
    - Neutron energy spectra at the lunar surface.
- In an Earth orbit with low geomagnetic shielding (e.g., geosynchronous orbit), the monitoring infrastructure should include spectrometers to measure the:
    - Energy spectra of protons from SPEs and GCR; and
    - Charge and energy spectra of GCR light and heavy ions.
- An infrastructure to monitor the global state of heliospheric energetic charged particles, propagating solar mass ejections and propagating shocks should include:
    - A minimum of 2 space-based white-light coronagraphs located in a "stereoscopic" configuration relative to the Earth-Sun line;
    - Solar wind plasma monitors, magnetometers, and energetic charged-particle spectrometers, covering a limited range of charge and energy, located at multiple points between 0.25 and 1 AU; and
    - A solar wind plasma monitor, magnetometer, energetic charged particle spectrometer, and space-based white-light coronagraph "upstream" of Earth at the L1 Lagrangian point.

SSSC Space Missions

Almost a decade ago solar scientists eagerly awaited the launch of the Solar and Heliospheric Observatory (SOHO), knowing that revolutionary improvements in the understanding of the Sun and energetic processes in its atmosphere required SOHO's new capabilities. Similarly, solar and heliospheric scientists eagerly await the launch of STEREO and Solar Sentinels missions in order to obtain the necessary revolutionary improvements in the understanding of the formation and propagation of interplanetary shocks in the solar wind and the acceleration and propagation of energetic charged particles associated with SPEs. Obtaining this revolutionary improvement in time to support long-duration human missions (e.g., extended lunar missions or a manned Mars mission), will require rephasing the Solar Sentinels mission so that it is operating by the next solar maximum.

Significant progress towards enabling human exploration missions can be made even before the development of new science missions by exploiting the capabilities of existing missions. Much benefit towards the development of GCR and SPE design models can be gained using existing International Solar-Terrestrial Program, Explorer, and other spacecraft. NASA should continue to operate the Advanced Composition Explorer (ACE), Ulysses, WIND, and Voyager spacecraft for the foreseeable future, and through the next solar maximum if possible.



Constellation of the current SSSC operating missions

Specific SSSC Space Mission Requirements

- The Solar Sentinels mission, providing solar wind plasma and energetic charged particle spectra measurements at multiple inner heliosphere locations inside 1 AU, should be rephrased in order to be operating and making measurements by the next solar maximum period.

- Extend the set of invaluable synoptic energetic charged particle measurements by continuing the valuable science provided by the ACE, Ulysses, WIND, and Voyager missions.

- Develop a plan to continue without interruption the synoptic solar wind plasma and energetic charged particle measurements that will inevitably stop when the ACE mission can no longer be sustained.

SUMMARY

Successfully achieving the goals set down in the "Vision for Space Exploration" requires active, focused support across all of NASA's enterprises. With its current and planned research portfolio, the Sun-Earth Connection program stands in a unique position to provide immediate, mid-term, and long-term support towards the successful return of humans to the Moon and the eventual human exploration of Mars. The LWS research program and assets are an integral component of the toolkit NASA must use to confront the health risks from exposure to space radiation so that humans can safely engage in exploration missions.

LWS's potential contribution to managing space radiation exposure risks fall into two categories: providing the measurements and physical understanding to enable the incorporation of prudent and efficient radiation protection strategies into the design of crew vehicles and mission plans; providing the physical understanding necessary for the development of operational radiation protection techniques and tools that will be used by flight support personnel during periods of high space weather activity.

Although current plans envision the first exploration missions to the Moon and Mars 10-15 years in the future, LWS's support should begin immediately through the continuation of on-going synoptic charged particle and plasma measurements by the ACE, Ulysses, WIND, and Voyager spacecraft. For the longer-term, LWS must ensure that the STEREO mission be accomplished on its current schedule; LWS should also give serious consideration to rephasing the Solar Sentinels program so that the mission's multiple spacecraft are operating by the next maximum of the solar activity cycle. As important as the future missions is the potential contribution over the near and mid-term by SSSC's TR&T program. The engineers and scientists involved with designing exploration spacecraft, habitats, and mission architecture, as well as supporting the actual missions, will be able to incorporate the optimal levels of radiation protection only through the continued support of research into theories of space weather dynamics, the development and evaluation of space environment design and forecast models, and the continued mining, analysis, and understanding of the rich treasure trove of existing space environment measurements.

The most notable gap in the current LWS program for meeting the necessary exploration mission support requirements is the lack of space plasma and energetic charged particle monitors upstream of Earth in the mid to long-term. For the past 7 years, this data has been provided nearly continuously by the ACE spacecraft, and there is hope ACE will continue to operate and collect data for perhaps another 5-10 years. At some point, however, ACE data collection will stop, resulting in the loss of these canonical measurements. LWS should begin investigating now options to continue making these essential measurements beyond the ACE era.

APPENDIX A

Living With a Star Exploration Initiative Workshop Panel Members

Michael Golightly (NASA Johnson Space Center)
Janet Barth (NASA Goddard Space Flight Center)
John Bieber (University of Delaware/Bartol Research Institute)
Frank Cucinotta (NASA Johnson Space Center)
Jim Garvin (NASA Headquarters /Code SE)
Tamas Gombosi (University of Michigan)
Steve Kahler (Air Force Research Laboratory)
Joseph Kunches (NOAA Space Environment Center)
Robert Lin (University of California--Berkeley)
Glenn Mason (University of Maryland)
Richard Mewaldt (California Institute of Technology)
Neil Murphy (NASA Jet Propulsion Laboratory)
Walter Schimmerling (NASA Headquarters /Code U)
Larry Townsend (University of Tennessee)
Jim Watzin (NASA Goddard Space Flight Center)
Paul Westmeyer (NASA Headquarters/Code SE)
John Wilson (NASA Langley Research Center)
Ron Turner (ANSER)
Michael Xapsos (NASA Goddard Space Flight Center)
Guy Fogleman (NASA Headquarters)

Ex Officio Members:
Richard Fisher (NASA Headquarters)
Lika Guhathakurta (NASA Headquarters)
Terri Lomax (NASA Headquarters)
Chris St. Cyr (NASA Goddard Space Flight Center)

APPENDIX B

Living With a Star Exploration Initiative Workshop Agenda

Workshop: Living With a Star Program and the Exploration Initiative

05 Apr 2004--Day 1

Overview

8:30	Everyone	5 min	Assemble and get seated
8:35	Golightly	15 min	Overview of group's purpose, areas to be addressed

Background

8:50	Fisher	30 min	LWS overview, including current and future assets/missions
9:20	Garvin	30 min	Lunar and Mars Robotic Exploration Programs
9:50	Watzin	20 min	Lunar missions

Exploration Mission Issues

10:10	Cucinotta	20 min	Exploration mission radiation issues--astronauts
10:30	*BREAK*	20 min	
10:50	Barth	20 min	Exploration mission radiation issues--hardware and electronics
11:10	Turner	20 min	Exploration mission radiation issues--space wx challenges intrinsic to the Moon, Mars, & beyond vision
11:30	Kunches	20 min	Space Weather Forecasting

Space Environment--Current Definition and Areas Requiring Further Research

11:50	Bieber	20 min	Design environment--GCR modulation and gradients in the heliosphere
12:10	Mewaldt	20 min	Design environment--GCR modulation and gradients in the heliosphere
12:30	LUNCH	90 min	
2:00	Mewaldt	20 min	Design environment--SPE gradients in the heliosphere and solar heavy ion intensities
2:20	Xapsos	20 min	Design environment--solar protons and heavy ions
2:40	Kahler	20 min	Design environment--SPE intensity
3:00	Gombosi	20 min	Global modeling of CME propagation (especially changes between Earth and Mars)
3:20	Townsend	20 min	Predicting intensity (exposure) of SPEs based on initial parameters
3:40	BREAK	20 min	
4:00	Cucinotta	20 min	Comparison of SPEs at Mars and Earth--results from MARIE

Radiation Protection and Operations During Exploration Class Missions

4:20	Bieber	20 min	Secondary radiations behind matter
4:40	Wilson	20 min	Exposures inside habitation modules and during EVAs
5:00	Golightly	20 min	Wrap-up--Plans for 2nd day
5:20	END OF FIRST DAY		

APPENDIX B (CONTINUED)

Living With a Star Exploration Initiative Workshop Agenda

Workshop: Living With a Star Program and the Exploration Initiative
06 Apr 2004--Day 2

Radiation Protection and Operations During Exploration Class Missions (cont)

8:30	Everyone	10 min	Assemble and get seated
8:40	Schimmerling	20 min	Space Wx monitoring and forecasting in support of exploration missions—requirements
9:00	John Wilson Richard Mewaldt	20 min	Space weather monitoring instruments at crew vehicle/habitat—requirements to ensure autonomous operations capability
9:20	Turner	20 min	Robotic precursor missions--measurements to advance future manned exploration missions

Space Weather/Space Radiation Issues

9:40	Everyone	60 min	Group discussion--what are the major space weather/space radiation issues that must be addressed for successful implementation of a manned exploration initiative
10:40	BREAK	20 min	
11:00	Everyone	60 min	Small group discussions--what research and support are needed to address issues (i.e., measurements, data, infrastructure, models, etc.)
12:00	LUNCH	90 min	
1:30	Everyone	60 min	Small group discussions--what research and support are needed to address issues (i.e., measurements, data, infrastructure, models, etc.)
2:30	BREAK	20 min	
2:50	Everyone	70 min	Group reports and discussions
4:00	Everyone	60 min	Wrap-up
5:00	END OF WORKSHOP		

APPENDIX C

Acronyms

ACE	Advanced Composition Explorer
AU	Astronomical Unit
BFO	Blood Forming Organ
Caltech	California Institute of Technology
CME	Coronal Mass Ejection
CRÈME	Cosmic Ray Effects on Microelectronics
EPACT	Energetic Particles: Acceleration, Composition and Transport
EVA	Extravehicular Activity (i.e., "space walk")
GCR	Galactic Cosmic Rays
Gev	Giga electron Volts
Gle	Ground-level event
GOES	Geostationary Operational Environment Satellite
HEAO	High Energy Astrophysics Observatory
HZE	High-Z and High-energy ion
IMP	Interplanetary Monitoring Platform
ISEE	International Sun-Earth Explorer
ISS	International Space Station
ISTP	International Solar-Terrestrial Probes
JPL	Jet Propulsion Laboratory
keV	kilo electron Volts
L1	First Lagrangian point
LET	Linear Energy Transfer
LWS	Living With a Star
MeV	Mega electron Volts
MeV/n	Mega electron Molts per nucleon
MHD	Magneto-Hydrodynamics
SAMPEX	Solar and Magnetospheric Particle Explorer
SEM	Space Environment Monitor
SEP	Solar Energetic Particle Event (same as SPE)
SEU	Single Event Upset
SMEI	Solar Mass Ejection Imager
SOHO	Solar and Heliospheric Observatory
SPE	Solar Particle Event (same as SEP)
SSSC	Sun-Solar-System Connection (formerly known as Sun-Earth Connection)
STEREO	Solar-Terrestrial Relations Observatory
Z	used to designate an ion's atomic number

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