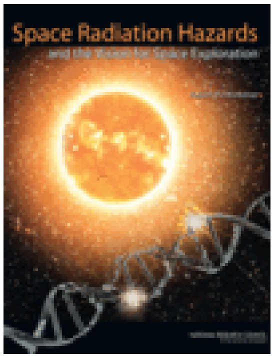

Space Radiation Hazards and the Vision for Space Exploration: Report of a Workshop

Ad Hoc Committee on the Solar System Radiation Environment and NASA's Vision for Space Exploration: A Workshop, National Research Council

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Advisers to the Nation on Science, Engineering, and Medicine

Space Radiation Hazards
and the Vision for Space Exploration

Report of a Workshop

Ad Hoc Committee on the Solar System Radiation Environment
and NASA's Vision for Space Exploration: A Workshop
Space Studies Board
Division on Engineering and Physical Sciences

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Preface

In October 2005 a group of approximately 120 experts on solar and space physics and the effects of radiation on humans and spacecraft met for a workshop at the Wintergreen conference facilities near Charlottesville, Virginia. This workshop followed other efforts by solar and space physics scientists to address ways in which their work could be focused on support for NASA's Vision for Space Exploration (see Box P.1). These earlier meetings included a RHESSI-SOHO-TRACE Workshop in December 2004[1] that had recommended a meeting near Washington, D.C., in the fall of 2005 to bring together NASA Exploration operations and engineering personnel and scientists. It also followed a workshop organized by NASA's Living With a Star (LWS) program, held on April 5-6, 2004, in Washington, D.C., to examine existing and planned LWS science missions that contribute to the enabling of proposed human lunar and Mars missions. At nearly the same time, the Committee on Solar and Space Physics (CSSP) of the National Research Council's (NRC's) Space Studies Board independently began planning for a study on space environmental hazards. The CSSP agreed to cosponsor the workshop and to prepare this NRC workshop report. A list of workshop participants and the agenda are provided in Appendix C.

The workshop participants made a significant contribution in helping to assess the current level of understanding of solar and space physics, in looking at some of the issues faced by the NASA space radiation program as it deals with radiation effects on humans, in focusing on the challenges of ensuring the reliable functioning of instruments and machines in space, and in illustrating how progress in understanding, defining, and, ultimately, making timely predictions of the space radiation environment is essential for implementation of the Vision for Space Exploration.

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[1] RHESSI, Ramati High Energy Solar Spectrographic Imager; SOHO, Solar and Heliospheric Observatory; TRACE, Transition Region and Coronal Explorer.

BOX P.1
NASA'S VISION FOR SPACE EXPLORATION

- Complete the International Space Station (ISS) by 2010
  - Research on ISS will focus on long-term effects of space travel on humans
- After ISS is complete, retire the Space Shuttle
- Begin developing a new vehicle for human exploration, the Crew Exploration Vehicle (CEV)
  - First crewed vehicle to explore beyond Earth orbit since the Apollo
  - Develop and test by 2008
  - First human mission for the CEV no later than 2014
  - Main purpose will be to leave Earth orbit; the vehicle will also ferry astronauts to and from ISS after shuttle retirement
- Return to the Moon by 2020, as launching point for missions beyond
  - Robotic probes to the lunar surface by 2008
  - Human mission as early as 2015—goal of living and working there for increasingly extended periods of time
- With the experience and knowledge gained on the Moon, take the next steps of space exploration: human missions to Mars and to worlds beyond

SOURCE: NASA, *The Vision for Space Exploration*, NP-2004-01-334-HQ, NASA, Washington, D.C., 2004.

Many of the participants at the conference had attended the April 2004 Living With a Star workshop and stated that there was a distinct change in attitude between that activity and the Wintergreen Workshop. At the Wintergreen Workshop many of the scientists recognized that there is significant overlap in interests between the solar and space physics community and the human spaceflight community and that the space physics community can assist in attaining the goals of the Vision for Space Exploration. Those communities had not cooperated closely before, but the Wintergreen Workshop demonstrated that such cooperation would be necessary in order to implement the Vision for Space Exploration.

This report addresses the importance of the following:

- The development of predictive and forecast tools by the solar and space physics community,
- Improved knowledge transfer of present scientific capabilities to the operational environment, and
- Continued close cooperation between space scientists and the radiation and health science communities.

This report provides a synopsis of the state of the art of the space weather elements related to human and robotic exploration missions. However, understanding solar and space physics continues to be a challenging problem in its own right, with high intellectual content that requires advances in physics, geophysics, and computation. NASA can ill afford to neglect to invest in this essential component of the agency's intellectual capital and, hence, its future.

The ad hoc committee thanks the many organizers and community members who helped to make this effort a success. It is the hope of the committee that the communities that came together for the Wintergreen Workshop will continue to work closely and cooperatively as the Vision for Space Exploration continues to evolve.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Timothy Bastian, National Radio Astronomy Observatory,
Anthony Chan, Rice University,
Philip Hahnfeldt, Tufts University School of Medicine,
Joseph Kunches, National Oceanic and Atmospheric Administration, and
George Paulikas, The Aerospace Corporation (retired).

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Eugene Parker, University of Chicago (emeritus professor). Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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APPENDIXES

Executive Summary

The President's Vision for Space Exploration (VSE) specifies that the United States should carry out a human lunar mission no later than 2020 and eventually conduct human expeditions to Mars. NASA has already been restructured to achieve these ambitious goals. This new policy creates many challenges, but not all of them are immediately obvious. Among these, the hazards of space radiation to crews traveling to the Moon and Mars will pose unique questions and challenges, not only to the spacecraft engineering community but to the space science community as well. Between the Apollo 16 and 17 missions in August 1972, for example, a powerful solar event occurred that would have seriously endangered astronauts on the lunar surface. Now that the United States has adopted a civilian space policy that refocuses many NASA research and engineering missions toward the human and robotic exploration of the Moon, Mars, and eventually other solar system bodies, events such as the powerful solar storms between Apollo missions over three decades ago must be interpreted in a new context.

Astronauts and spacecraft participating in the VSE will be exposed to a hazardous radiation environment, made up of galactic cosmic radiation and driven by solar energetic particle events and "space weather" changes. Accurate and timely information about this environment is required in order to plan, design, and execute human exploration missions. The information required consists of estimates or measurements of the time of occurrence, duration, and spatial distribution of the radiation, as well as the type, maximum intensity, and maximum energy of the constituent particles. Unfortunately, the prediction and forecasting of solar activity and space weather are severely hampered by a lack of understanding of how the Sun affects the heliosphere and planetary environments of Earth, the Moon, and Mars. Scientific progress in this field, leading to accurate long-term and short-term predictions of the space radiation environment, is required if solar and space physics scientists are to make the significant contribution required of them by human exploration missions.

A workshop held on October 16-20, 2005, in Wintergreen, Virginia, and cosponsored by NASA, the National Science Foundation, and the National Research Council brought together members of the space science, planetary science, radiation physics, operations, and exploration engineering communities. (The list of workshop participants and the agenda are presented in Appendix C.) The objectives of the workshop were to increase awareness and understanding of the complex array of solar and space physics issues pertinent to the environments of Earth, the Moon, and Mars; to identify compelling research goals necessary to ensure the success of the Vision for Space Exploration in these environments; and to discuss the directions that research in these fields should take over the coming decades in order to achieve these goals. The workshop effectively recognized that a multidisciplinary approach to defining the challenges of human exploration is required because no single National Academy of Sciences decadal survey or combination of surveys provides the type of advice needed for the new programs that are anticipated under the Vision for Space Exploration. Also, no single scientific or engineering discipline can provide the expertise and knowledge necessary to solve these problems optimally.

The workshop placed particular emphasis on the following topics:

- The heliospheric radiation environment as understood to date, including required data sources and possible new measurements;
- Physical mechanisms of energetic particle acceleration and transport in the heliosphere as understood to date;
- Radiation health hazards to astronauts;
- Radiation effects on materials and spacecraft systems; and
- Mitigation techniques and strategies, including forecasting and operational schemes.

A central theme that emerged during the workshop, both in the formal presentations in the plenary sessions and in focused discussions in thematically organized working groups, is the importance of the timely prediction of the radiation environment for mission design and mission operations. **There was general agreement among the participants that it is in this area that the solar and space physics community can, through improved characterization and understanding of the sources of space radiation, contribute substantively to NASA's radiation management effort and to the Vision for Space Exploration.** This statement may seem self-evident, but many workshop participants noted that it represented a change in attitude from previous community meetings. During the workshop, many of the participants focused for the first time in decades on ways that their research corresponds with NASA's needs to support humans traveling beyond low Earth orbit. Among the points that the workshop participants agreed on were the following:

- Developing timely predictions of the radiation environment is a complex task whose components vary depending on the timescale considered and on the mission characteristics;
- Delivering timely predictions requires advances in basic space and solar physics, development of observational assets, improved modeling capabilities, and careful design of communications;
- The space operations community—that is, those who plan and manage human spaceflight missions—must be informed about these advances in understanding and expanding capabilities so that operators can take advantage of advances; and
- In some cases operational tools (i.e., tools for space operations) must be developed or adapted from scientific analytical tools and converted to real-time reporting tools; the transition from research to operations is a very challenging task.

The workshop effectively assessed the following topics: the current level of understanding of solar and space physics; the issues faced by the NASA space radiation program as it deals with radiation effects on humans; the challenges of ensuring the reliable functioning of instruments and machines in space; and how progress can be made in understanding, defining, and, ultimately, making timely predictions of the space radiation environment.

Workshop participants made clear that current or planned research tools could be adapted to support the implementation of the Vision for Space Exploration. There was great enthusiasm about the ability to contribute to this endeavor. Rather than developing entirely new hardware or products, the space operations community can exploit many existing assets. However, many of the workshop participants also expressed the concern that a primary challenge will be knowledge transfer—that is, arranging existing data sets, models, research tools, and other assets in ways that make them useful to the space operations community. The solar and space physics community and the human spaceflight operations community do not have extensive existing ties, and this lack presents a barrier to effective collaboration. Better communication between these communities must be established; it will provide substantial benefits. Many workshop participants stated that NASA should conduct future interdisciplinary meetings similar to the Wintergreen Workshop to help coordinate the work of scientists and operators.

The nature of the workshop as an interdisciplinary forum demonstrated how it was possible that the space operations community might benefit from completely unexpected sources of data that it might never have realized existed except for such a collaboration. For example, recent studies of historical data from polar ice core samples suggest that solar events much larger than the August 1972 event have occurred during the past several hundred years. The largest of these events appears to have been the Carrington event of 1859. Estimates of possible organ doses from an event of this magnitude (~4 times larger than occurred in August 1972) indicate that substantial shielding would be needed to protect human crews in space. Astronauts performing extravehicular activities in space or surface exploration activities on the Moon during an event of this magnitude could receive potentially lethal exposures. Because NASA is contemplating stays on the lunar surface that may eventually last up to 6 months, there is a much higher probability of crews being exposed to a significant solar event than during the much shorter Apollo missions (which lasted no longer than 2 weeks from launch to landing).

Knowledge of the space radiation environment of the past provides the historical context for understanding the space radiation environment of the present. However, it also requires caution in extrapolating from present conditions to those that might exist in the future. With respect both to galactic cosmic radiation (GCR) intensity and to the frequency with which large solar energetic particle (SEP) events occur, the radiation environment at 1 AU appears at present to be relatively "mild." The historical record suggests that this is unusual and that if this mild interregnum ends, there might be significant consequences for human exploration.

Given the significant contribution of GCR to total radiation exposure of astronauts, it is important to understand long-timescale (decades or more) variations in the GCR. It is well established that at short timescales (months to years) the GCR flux varies with solar activity, peaking at solar minimum. But over longer timescales, the solar cycle amplitudes also vary. Some solar maxima are more intense than others. During a period known as the Maunder minimum, the number of sunspots, a measure of solar activity, essentially dropped to zero; hence the GCR flux would have been greater. What happens to the GCR intensity at such times? Recent solar cycles have had relatively large amplitudes, suggesting that the present may be a period of relatively low peak GCR intensities.

The workshop showed that a multidisciplinary approach could potentially reduce the costs of separate research efforts through the sharing of information. The information needed to meet solar and space physics objectives and to meet the requirements of the radiological health program often overlap. However, the priorities of the two areas generally differ. For example, a solar and space physics objective may require detailed particle energy resolution over a limited range of particle energies, while radiological health measurements require data for a broader range of energies but do not require the high resolution. Consequently, the data analysis phase of many solar and space physics experiments, constrained by budget limitations, did not recover all of the available information relevant to radiation protection. As a result, significant information relevant to radiological health may be available for a modest investment in the further analysis of existing data sets. Similarly, minor modifications to proposed solar and space physics instruments may result in data that will meet radiological health protection requirements, thereby eliminating the need for additional instruments intended solely for health protection measurements.

The Vision for Space Exploration raises important questions about how to determine that the knowledge base and predictive capabilities are adequate to commit crews to even longer missions to Mars. Currently, NASA's regulations governing acceptable radiation doses for human crews in low Earth orbit are for intervals significantly less than the 1,000 days it would take to send a crew to Mars. This limit is established by taking into account many poorly understood biological factors, and NASA is making progress toward reducing the size of the uncertainties. As several workshop participants noted, merely reducing the amount of uncertainty in the understanding of radiation health effects can significantly increase the number of days allowable for human crews to spend in space. But NASA will have to make a concerted research effort to reduce that uncertainty; it will not happen without planning.

Space radiation not only affects humans but can affect spacecraft, instruments, and communications as well. Some of these effects are well known, such as electrostatic charging and degradation of solar cells. Solar particles, cosmic rays, and trapped particle radiation are all of concern in this regard. Certainly a reduction in uncertainty about such radiation will improve spacecraft design and operations.

Global radiation models are beginning to become available, but they are difficult to tailor to specific events. One clear statement from the workshop is that there is a need for a better understanding of how to relate solar and space physics observations to the models. The observations have a dual role: (1) they provide the inputs to drive models, and (2) they are required to validate the models (post facto). For the near-term need, it should be possible to improve predictions of "all clear" periods when there is a very low probability that an SEP event will occur. This is possible with a better understanding of the signatures indicating that a flare or coronal mass ejection is about to erupt. New observations of solar magnetic structures with Solar-B, the Solar Dynamics Observatory, and the ground-based Advanced Technology Solar Telescope and the Frequency Agile Solar Radio Telescope will help in this regard.

Farther in the future, it is desirable to make predictions of solar events days to weeks before they occur. Initially, this will be possible only with models that use a statistical approach along with a suitable set of in situ and remote sensing measurements from multiple vantage points in the heliosphere. It will be most useful for the Vision for Space Exploration if models can predict the following: (1) the onset time for an SEP event, (2) its time-intensity profile, (3) the "spectral indices" of the energy spectrum, (4) the shock arrival time, and (5) the anisotropy in the particle velocity distribution (a lower priority). An effective warning system for SEP events will require an operational distributed network of observations from the Sun throughout the heliosphere (similar to the distributed network of weather stations on Earth). Near-Sun missions such as Inner Heliosphere Sentinels, Solar Orbiter, and Solar Probe will provide unique measurements to test more sophisticated models. Recent physics-based (dynamo) models of the Sun give hope of making accurate predictions of the size of solar activity cycles years or decades in advance.

Because of the threat posed by SEP events, taking radiation safety into account will be critical in order to ensure adequate shielding or timely access to a safe haven. Fortunately, awareness of the risk of radiation exposure is widespread, and it is hoped that systems will be designed to manage radiation risk. It is critical to decide at the outset what the radiation risk mitigation strategy will be and then to integrate this strategy into the mission concept early in the design phase. The generic elements of a radiation risk mitigation strategy include space environment situational awareness, radiation exposure forecasting, and exposure impact and risk analysis. These elements combine to generate recommendations to the mission commander, who has the responsibility for keeping the radiation exposure as low as reasonably achievable.

The large uncertainties in space radiation and biological effects that exist at present increase the cost of missions owing to the large safety margins required as a consequence. These uncertainties also limit the ability to judge the effectiveness of risk mitigation methods, such as improvements in shielding or biological countermeasures. Operational measures and radiation shielding are currently the main means of reducing radiation risk; improved biological markers have the potential to enable improved early diagnostics; discovery of means of biological prevention and intervention may lead to significantly more powerful methods, including better radioprotectants, to overcome the biological consequences of exposure to radiation. Continued basic research has the potential to address all of these key issues effectively.[1]

The challenges described here can be overcome, and NASA is making progress on many of them. But the hazards of space radiation to future space explorers can only be reduced with the assistance of the solar and space physics science community and effective collaboration between the scientists and the space operations community.

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[1] Extraordinary shielding (~300 to 500 g/cm^2) would be necessary to protect astronauts if their radiation limits were set at levels comparable to those of occupationally exposed individuals on Earth (e.g., workers at nuclear power plants) or at the even lower exposure limits established for the general public. However, astronaut limits for operations in low Earth orbit (LEO) are approximately an order of magnitude higher than limits for earthbound radiation workers (at present 50 centi-sievert [cSv] per year for astronauts, with a lifetime limit that depends on age and sex; however, no limits have been established as yet for Mars missions). This difference is due to the shorter career exposure times for astronauts (generally assumed to be no more than 10 years) versus possible 40+ year career exposure times for radiation workers on Earth. The LEO limits for astronauts, although higher than limits for earthbound radiation workers, are based on a 3 percent excess cancer mortality risk. Shielding needed to attain this elevated level of permitted exposure is much less than the heroic value of 300 to 500 g/cm^2, generally being somewhere in the range of 20 g/cm^2 or somewhat above. For example, for 20 g/cm^2 aluminum shielding, Townsend et al. (1992) calculate 50 cSv per year at solar minimum, but Cucinotta et al. (2005) now estimate closer to 75 cSv/year using the newer transport codes and environmental models. The effect of these levels on astronaut risk is not sufficiently well known at this time and is a subject of active research. Future human spaceflight depends on the outcome of this research. Note that the most relevant radiation protection quantity is the radiation risk, as represented by the dose equivalent, which represents risk of developing a fatal cancer. Most of the dose equivalent is contributed by the heavy ion component of the GCR spectrum and not the protons. Dose is important, but only for possible acute radiation syndrome effects (radiation sickness) resulting from very large SEP radiation exposures. Dose is relatively small from GCR particles, being only around 20 centi-gray (20 rads) annually during solar minimum, of which only about 7 rads come from protons of all energies (Townsend et al., 1992). "Gray (Gy)" is the name for the unit joule per kilogram when that unit is applied to the absorbed dose. "Absorbed dose" is defined as the energy imparted by ionizing radiation per unit of mass.

1

Radiation Risks and the Vision for Space Exploration

On April 27, 1972, the crew of Apollo 16 returned to Earth from a lunar exploration mission that lasted 11 days. Slightly more than 3 months later, on August 4, 1972, the largest solar energetic particle (SEP) event of the 22nd solar cycle commenced. Significant fluxes of high-energy protons began arriving at 1 AU less than 40 minutes after a major optical solar flare was observed. This event was also one of the largest and most dangerous of the space era. Four months after the event, on December 7, 1972, Apollo 17 was launched and began the final lunar exploration mission of the Apollo era.

In the ensuing three decades, various studies of the possible absorbed doses from this August 1972 event and their potential biological effects on human crews have been carried out (e.g., Wilson and Denn, 1976; Townsend et al., 1991, 1992; Wilson et al., 1997; Parsons and Townsend, 2000). In these studies, skin doses as large as 15 to 20 Gy[1] were estimated behind shielding comparable in thickness to that provided by a spacesuit. Skin doses of this magnitude, delivered in less than a day, with dose rates as high as 1.5 to 2.0 Gy h^{-1}, could have resulted in severe skin damage, including skin blistering and peeling. Even inside a spacecraft, skin doses as large as 2 Gy would have been possible. In addition, bone marrow doses at ~1 Gy could have been received by the crew, resulting in some hematological responses, including blood count changes and possibly nausea or vomiting inside a spacesuit or typical spacecraft. Clearly this event could have had severe consequences for either Apollo 16 or 17 if it had occurred during either of these missions.

Recent studies of historical data from polar ice core samples suggest that events much larger than that of August 1972 have occurred during the past several hundred years (see Box 1.1, "Long-Term Radiation Studies: The Ice Core Evidence"). The largest of these events appears to be the Carrington event of 1859. Estimates of possible organ doses from an event of this magnitude (~4 times larger than that of August 1972) indicate that substantial shielding would be needed to protect human crews (Townsend et al., 2005). Crew members performing extravehicular activities in space or surface exploration activities on the Moon during an event of this magnitude could receive potentially lethal exposures. It is also problematic that,

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[1] "Gray (Gy)" is the name for the unit joule per kilogram when that unit is applied to the absorbed dose. "Absorbed dose" is defined as the energy imparted by ionizing radiation per unit of mass.

BOX 1.1
LONG-TERM RADIATION STUDIES: THE ICE CORE EVIDENCE

The variability of both galactic cosmic radiation (GCR) and solar energetic particles (SEPs) with the Sun's ~11 year activity cycle has been well established on the basis of direct measurements made over the past 70 years, first from the ground and later with ground-based and space-based instruments. It has been known since the early 1960s that GCR fluxes are modulated by the interplanetary magnetic field (IMF) and are anticorrelated with solar activity, with the lowest fluxes occurring when solar activity is highest and vice versa (Figure 1.1.1).

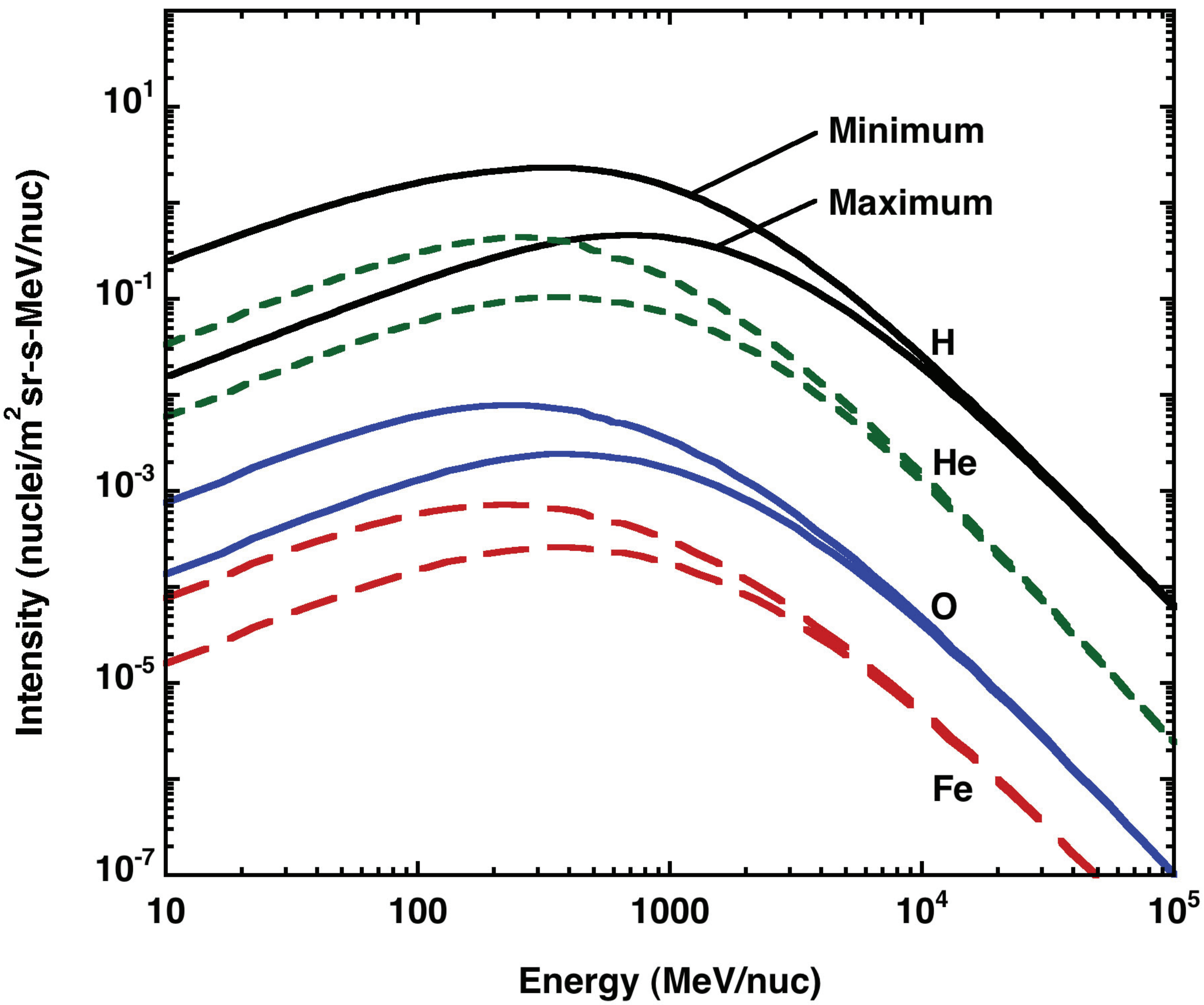

FIGURE 1.1.1 Representative galactic cosmic ray ion spectra depicting the intensity variations between solar maximum and solar minimum conditions. The upper curve for each species is for solar minimum, when cosmic rays can penetrate into the inner heliosphere more easily. SOURCE: Courtesy of R.A. Mewaldt, California Institute of Technology.

In contrast, SEP events occur roughly in phase with the solar cycle, with proportionally more events late in the cycle and very significant variations from cycle to cycle. Within this overall statistical pattern, SEP events are unpredictable and can occur at any time during the solar cycle.

Other patterns of short-term variability have been discovered as well: an approximately 22 year cycle in the shape of the GCR peak, for example, and a 27 day modulation of galactic cosmic radiation intensity related to the Sun's rotational period. But while reliable, continuous direct measurements have made it possible to characterize the temporal behavior of GCR and SEPs within the modern era (as defined by the availability of such measurements), they cover too short a time period to capture longer-term, secular variations that are also important for an understanding of the space radiation environment and the solar processes that influence it. Fortunately, however, when galactic cosmic radiation and solar energetic particles interact with Earth's atmosphere, they trigger nuclear and chemical reactions, the products of which, deposited and preserved in the polar ice, provide a record of cosmic radiation modulation and SEP activity that extends centuries, even millennia, into the past.

One of the key products of this process is the ^{10}Be isotope, which attaches itself to aerosols and, after a residence of several months in the atmosphere, precipitates onto Earth's surface. In the polar regions, the precipitated ^{10}Be is preserved in the successive layers of ice that build up over the centuries and that record the history of the local meteorology and of the global influences on it. By boring into the polar ice and extracting core samples from it, researchers can analyze the composition of the different ice layers and measure the amount of ^{10}Be deposited in each. Because ^{10}Be production is proportional to the cosmic radiation flux and because the isotope has a long half-life (1.5×10^6 years), the variations in the ^{10}Be concentration measured in the ice layers can be used to reconstruct the changes in the GCR flux over periods of several millennia.

Analysis of ^{10}Be data has shown that GCR intensities were high though variable during extended periods of low solar activity in the past, such as the Spoerer (1420 to 1540 CE) minimum and the last part of the Maunder (1645 to 1715 CE) minimum. (The level of solar activity in the past is inferred from reports of auroral activity, which date back to the 11th century, and from the sunspot record, which has been kept since around 1600.) The variations in the ^{10}Be concentrations for these periods indicate that—at times substantial—modulation of the GCR fluxes can continue even during periods of low solar activity and that, as in the case of the Maunder minimum, the modulation is not necessarily well correlated with the sunspot number. Further, comparison of GCR intensities in the modern era with those deduced from the ^{10}Be data for earlier epochs indicates that during the past half century, the GCR intensity near Earth has been one of the lowest in the past 1150 years (Figure 1.1.2, McCracken et al., 2004).

Nitrate (NO_3) is a product of the chemistry initiated by the interaction of solar energetic particles with Earth's upper atmosphere. Like ^{10}Be, it is removed from the atmosphere by precipitation and accumulates in the polar ice, although on a much shorter timescale (<1.5 months versus ~1 year). It has recently been demonstrated (McCracken et al., 2001a) that spikes in the concentration of NO_3 in polar ice cores provide a record of past large SEP events, just as ^{10}Be data provide a means of deducing the GCR environment in earlier epochs for which direct measurements are not available. Reconstruction of past SEP events from ice core data has revealed that large events (those with fluences $>2 \times 10^9$ cm^{-2} for particles with energies >30 MeV) occur

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**BOX 1.1
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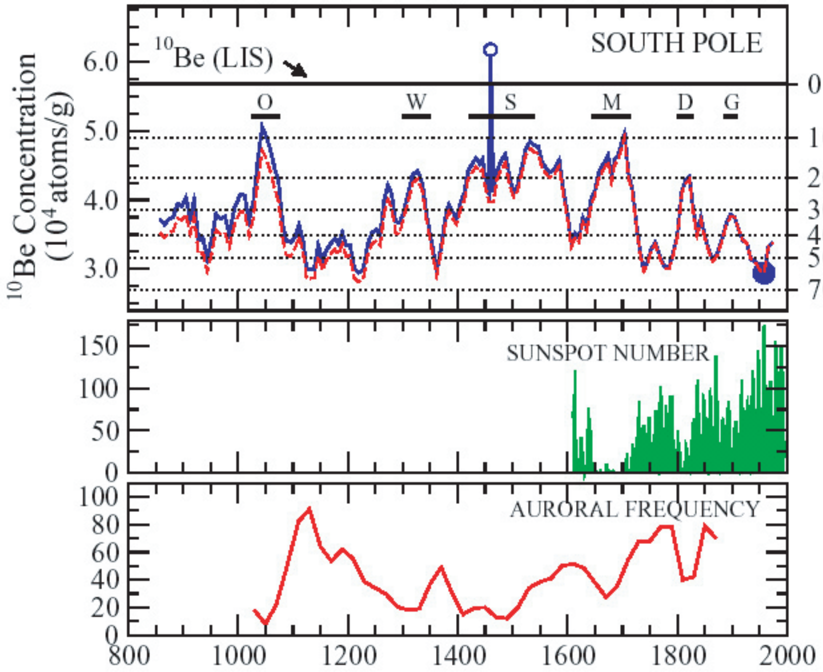

FIGURE 1.1.2 ^{10}Be concentrations measured in ice core samples from the South Pole provide a record of the variability in the GCR flux at 1 AU for the period 850 CE to 1958 CE. Intensities are highest during secular minima in solar activity, as denoted in the top panel by the letters and bold horizontal bars and indicated in the second and third panels by the sunspot number and auroral frequency, respectively. (O = Oort minimum; W = Wolf minimum; S = Spoerer minimum; M = Maunder minimum; D = Dalton minimum; and G = Gleissberg minimum.) SOURCE: McCracken et al., 2004. Copyright 2004, American Geophysical Union. Reproduced by permission of American Geophysical Union.

with an approximately 80 year period (the Gleissberg cycle). The frequency with which large events occurred during earlier epochs was 6 to 8 times greater than the frequency of SEP events during the period from about 1960 to the present, which appears to be the minimum of the Gleissberg cycle that began circa 1910 (Figure 1.1.3, McCracken et al., 2001b).

Knowledge of the space radiation environment of the past provides the historical context for an understanding of the space radiation environment of the present and urges caution in extrapolating from present conditions to those that might exist in the future. With respect both to GCR intensity and to the frequency

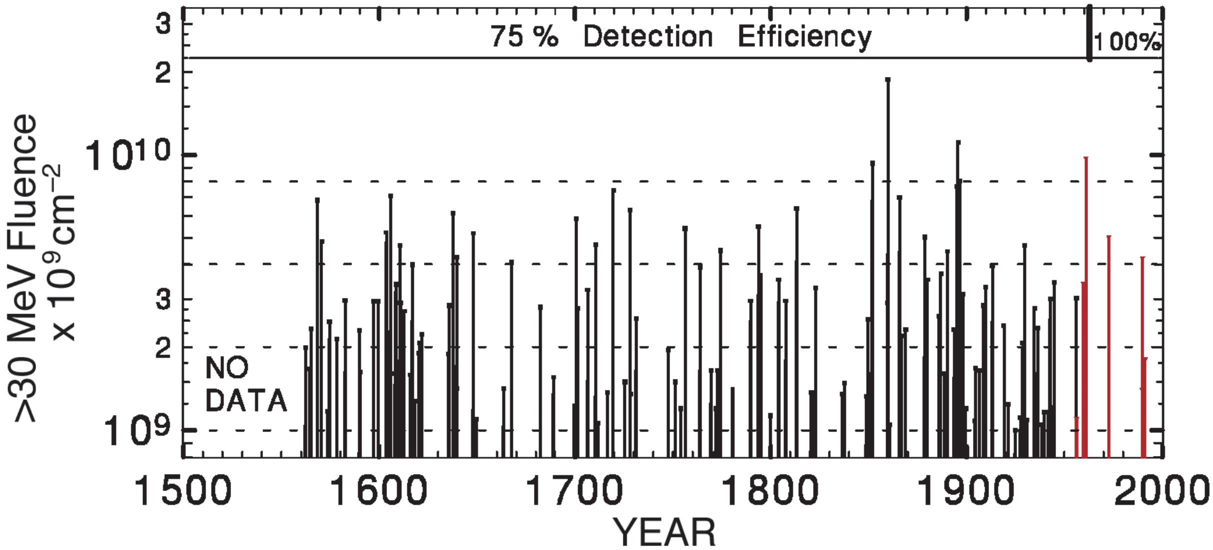

FIGURE 1.1.3 Spikes in the NO_3 concentration in Greenland ice core samples converted to proton fluences (black vertical lines) document the occurrence of large fluence solar energetic particle events over a period of nearly four and a half centuries beginning in 1561. Proton events that were detected directly between 1965 and 2000 are indicated by the red lines. SOURCE: Smart et al., 2006, based on McCracken et al., 2001b. Reprinted from D.F. Smart, M.A. Shea, H.E. Spence, and L. Kepko, 2006, Two groups of extremely large >30 MeV solar proton fluence events, pp. 1734-1740 in *Advances in Space Research,* Vol. 37, copyright 2006, with permission from Elsevier.

with which large SEP events occur, the radiation environment at 1 AU appears at present to be rather "mild." However, the historical record suggests that it might not remain so in the future, with significant consequences for human exploration. As McCracken et al. (2001b) point out, "Satellite engineering practice uses the [solar particle event] and related solar-terrestrial characteristics for solar cycles 20–22 to determine engineering and commercial risk in addition to operational lifetimes. A return to the high solar proton event rates observed at the maxima of the Gleissberg periodicity . . . would have substantial impact on space engineering and space travel." A similar statement could be made with respect to the galactic cosmic radiation environment.

Analysis of the ^{10}Be and nitrate data not only makes possible the characterization of the past radiation environment at 1 AU; the picture of secular trends in GCR modulation and SEP occurrence derived from the ice core data also serves as an invaluable source of information about solar activity and heliospheric conditions over timescales of millennia, information not available from any of the other historical data records.

because of the current limit of knowledge about radiation hazards, NASA's current rules for acceptable risk in Earth-orbital operations for astronauts at the 95 percent confidence level would not allow a crew to stay in space for the length of time necessary to perform several space exploration missions, such as a human-to-Mars mission. NASA determines this level by using a statistical assessment of the uncertainties in the risk projection to limit the cumulative weighted dose (dose equivalent in units of sievert) received by an astronaut throughout his or her career.[2]

Following the presidential space policy announcement of the Vision for Space Exploration (VSE) in January 2004,[3] NASA embarked on a long-term human and robotic space exploration effort that will include human missions to the Moon and Mars. Science to enable human exploration is inherently multidisciplinary, involving insights from many fields of science and technology. All of the past science strategy studies have been, by design, discipline-based. That is, they have provided scientific goals and priorities for a particular field or set of related disciplines. This approach to setting scientific goals for breakthroughs in individual fields is effective, and the current National Research Council (NRC) reports remain timely and relevant today in their respective areas.

However, NASA's new Vision for Space Exploration opens up novel and previously unexplored issues whose nature can best be illustrated by the question, *How, and by whom, is the decision to be made that the necessary medical, scientific, and technological knowledge has been acquired before the United States actually sends humans to Mars?* No single NRC decadal survey or combination of surveys provides the type of advice needed for the new programs that are anticipated under the new VSE. **Also, no single scientific or engineering discipline can provide the expertise and knowledge necessary to solve these problems optimally. Therefore, a reexamination of the decadal surveys has not provided ideal guidance for enabling science. Instead, crosscutting advice needs to come from cross-disciplinary groups of experts representing diverse scientific fields rather than from the traditional single-discipline advisory committees. The problem of understanding and mitigating the effects of space radiation is a prime example of such a crosscutting issue.**

Understanding and mitigating the deleterious effects of space radiation on both astronauts and operational systems constitute a complex, multifaceted problem. Progress in countering the harmful effects of different space radiation environments has to draw on advances in solar and space physics, radiation monitoring, risk assessment, materials science, biomedical science, medical systems engineering, space systems design, and other areas. It also will be facilitated by the use of robotic "guinea pigs" rather than human subjects. A piecemeal approach to planning research and setting priorities under the guidance of individual scientific disciplines is unlikely to produce robust, reliable solutions. Therefore, there is a need, both internally in NASA and in the broader scientific and space operations communities, to foster a multidisciplinary approach.

THE SPACE RADIATION ENVIRONMENT

There are three main natural sources of radiation in space to which spacecraft and astronauts may be exposed: (1) galactic cosmic radiation (GCR), (2) solar energetic particles (SEPs), and (3) energetic particles trapped in a planetary magnetic field. Anomalous cosmic rays, accelerated at the solar wind termination, are judged not to pose a hazard. An additional important source of radiation are the secondary neutrons

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[2] A sievert unit is the amount of ionizing radiation dose equivalent required to produce the same biological effect as 100 rads of high-penetration x-rays.

[3] The Vision for Space Exploration initiative was announced by President George W. Bush on January 14, 2004, and is outlined in *The Vision for Space Exploration* (NASA, 2004).

produced by the interaction of energetic particles with a planetary atmosphere or surface (Clowdsley et al., 2001; Keating et al., 2005).

Galactic Cosmic Radiation

Galactic cosmic rays are highly energetic nuclei (mainly in the range 100 MeV per nucleon to 10 GeV per nucleon) believed to be accelerated at shocks produced by supernova explosions. GCR consists predominantly of protons, with alphas (He nuclei) as the next most abundant species. Trace numbers of heavier nuclei such as carbon, oxygen, and iron are also present. Although high Z energetic (HZE) particles are only a tiny fraction of the GCR population, they are of particular concern because they are highly ionizing and their biological effects are uncertain. (The rate of energy transfer from a GCR to the ionization of the background matter is proportional to Z^2, where Z is the charge of the GCR particle.) Once GCR has entered the solar system, its fluxes are modulated by the solar wind and the heliospheric magnetic field, so that there is an 11 year periodicity in GCR intensity, with the most intense fluxes occurring in antiphase with solar activity. There are 27 day and 22 year periodicities in the GCR flux also observed. In addition, recent analyses of ice core data (see Box 1.1) have revealed longer-term variations in GCR intensity as well and suggest that the present GCR intensity may be anomalously low.

Solar Energetic Particles

Solar energetic particles are produced both by solar flares and by shocks driven by fast coronal mass ejections (CMEs). In large SEP events, both flare-accelerated and CME-accelerated particles are generally present, with the flare-accelerated populations characterized by ^{3}He and heavy-ion abundances that are enhanced relative to coronal values. While smaller, impulsive, flare-associated events can occur at any time during the solar cycle, larger SEP events occur most frequently during periods of increased solar activity. Unusually intense, “worst case” SEP events occurred in February 1956, August 1972, and September 1989. Such events appear to be relatively uncommon in the present era but may have occurred with appreciably greater frequency in the past (see Box 1.1). As previously noted, the most powerful SEP event known to date occurred in 1859, with an estimated >30 MeV proton fluence of 18.8×10^9 cm^2 (McCracken et al., 2001a).[4]

Earth’s magnetic field shields against GCR and SEPs, although imperfectly. The field in the polar regions is open to both GCR and SEPs; during intense magnetic storms, the region of open flux expands, allowing access for precipitating SEPs to lower latitudes. Galactic cosmic rays with sufficient rigidity impinge on the atmosphere at middle and low latitudes as well as at the poles. It is outside the magnetosphere, however, in interplanetary flight and on the surfaces of the Moon or Mars, that both kinds of radiation will present the greatest risk to astronauts.[5]

While GCR is the dominant source of radiation to which astronauts on lunar or interplanetary missions will be exposed, the GCR background and its modulation by solar activity and the interplanetary magnetic field (IMF) are relatively well understood and predictable (Badhwar and O’Neill, 1992). The principal unknowns in this case are the effects of the interaction of HZE particles with shielding materials and human tissue. In contrast, SEP events are episodic; are highly variable in composition, intensity, spectra, and temporal profile; and thus are difficult to predict. Despite the advances in knowledge and understanding

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[4] According to Davis (1982), though recorded separately by two persons located some miles apart, this event is known as the “Carrington event” after the English astronomer Richard Carrington.

[5] The rigidity of an energetic charged particle is defined as the ratio of momentum to charge (momentum/charge) and is a measure of the particle’s ability to penetrate a magnetic field.

of SEP events made possible by Advanced Composition Explorer (ACE) and Ulysses data, there remain a number of fundamental questions about SEP acceleration, propagation, and the physical conditions (e.g., seed populations, IMF configuration, shock speed, and geometry) that influence the properties of SEPs observed at 1 AU. Answering these questions is a necessary condition for the development of a predictive capability useful for operational purposes.

Trapped Radiation

All of the magnetized planets have populations of highly energetic particles that are trapped in the planetary magnetic fields. The most extensively studied of these trapped populations are Earth's radiation belts (the Van Allen belts) and the radiation belts of Jupiter. The region of trapped radiation within Earth's magnetosphere consists of energetic protons, electrons, and heavy ions organized in two belts, a relatively stable proton-dominated inner belt and a highly variable electron-dominated outer belt. Energies range from ~100 keV to >400 MeV for protons and from 10s of keV to >10 MeV for electrons. Manned missions in geospace are flown in low Earth orbit, at altitudes below the inner belt[6]; however, astronauts embarking on or returning from journeys to the Moon or Mars will have to pass through the Van Allen belts and will be exposed for brief periods to high levels of radiation.

Secondary Radiation

Galactic cosmic rays and SEPs impinging on the atmosphere or surface of a planet or satellite produce secondary radiation, including energetic neutrons, which may contribute significantly to the surface radiation environment to which astronauts would be exposed. Modeling studies of the radiation environment at the surface of Mars (e.g., Wilson et al., 1999; Clowdsley et al., 2001; Wilson et al., 2004) have shown that, in addition to the spectra and fluence of the primary particles, the factors that determine the intensity of the secondary radiation produced are the density of the atmosphere and the composition of the surface, with a higher neutron yield from the dry regolith than from regolith covered with frozen CO_2 or water ice. Characterization of the martian surface radiation environment through in situ measurements is required in order to validate the transport codes used in such studies; it is one of the core science objectives of the Mars Science Laboratory mission.

RADIATION RISKS

NASA is required by law to limit radiation exposure to humans in space and to implement appropriate risk mitigation measures in order to ensure that humans can safely live and work in the space radiation environment, anywhere, anytime. In this context, "safely" means that acceptable risks are not exceeded during crew members' lifetimes, where "acceptable risks" include limits on postmission and multimission consequences (e.g., excess lifetime fatal cancer risk).

The risks associated with exposure to radiation cannot be measured directly. What is measured, or calculated, is an ensemble of physical data characterizing the radiation field. There are significant uncertainties in the relationship between the physical quantities and the risk. The most commonly used physics information is the absorbed dose, D. The absorbed dose is defined as energy deposited per unit mass, in

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[6] Its 51.6 degree inclination orbit takes the International Space Station to high geomagnetic latitudes where it may be exposed to increased relativistic electron and SEP fluxes during major space weather disturbances. The GCR fluxes are also higher at these latitudes than in a low-inclination orbit. See the NRC (2000) report *Radiation and the International Space Station: Recommendations to Reduce Risk*.

human tissue, at a microscopic level small enough to neglect the distortion of the field by the surrounding material, but large enough to neglect the effect of statistical fluctuations in energy deposition. This differs conceptually from the more commonly considered product of the fluence and stopping power, because the energy lost by incident radiation may be distributed over a much larger volume; however, in many common irradiation situations, the difference between absorbed dose obtained using stopping power and absorbed dose corrected for local deposition and energy fluctuations is not significant. Analog instrumentation ("dosimeters") with calculated corrections generally provides an adequate estimate of radiation dose.[7]

The dose can also be calculated using measured or calculated characteristics of the radiation field. In that sense, all physical measurements and models intended to provide input for risk estimates are broadly referred to as dosimetry. The properties of charged-particle radiation of greatest importance are the atomic number, Z; the atomic weight, A; the energy per nucleon, E/A (a measure of the nucleus velocity); the number of particles traversing a given surface, or fluence, ϕ the direction of incidence; and the flux, or fluence per unit of time. The quantities can be used to calculate the ionization properties of each particle, that is, stopping power or some version of linear energy transfer (LET). The heavy charged particles under consideration have a sharply defined trajectory in matter, proceeding mostly in a straight line until they have lost all their energy and come to a stop. The distance traversed is the range, which can also be calculated from their physical properties. When these particles traverse matter they undergo nuclear reactions. The resulting radiation fields inside spacecraft are substantially different from those in free space, and include neutrons as well as charged secondaries (Wilson et al., 1991).

The microscopic nature of energy deposition becomes important in the case of heavy charged particles, since the dose close to the particle track can be several orders of magnitude greater that the dose averaged over an entire cell or cell nucleus, and the same dose delivered by different types of radiation can lead to different biological effects. For such types of radiation, the dose is weighted by an appropriate factor reflecting the greater effectiveness of the type of radiation, for example, heavy charged particles or neutrons. The limiting risk is often cancer mortality; in that case, the weighting factor is prescribed by regulatory agencies and is referred to as the *quality factor*. Other weighting factors are used to convert dose from different types of radiation, risk to different organs, and corrections for various other factors involved in the calculation of risk into a common scale proportional to risk.

These data are then used to calculate the risk. Risk is a stochastic variable, corresponding to a probability distribution of observing all significant health effects arising out of exposure to radiation in space. Such risk estimates are based on models of biological responses at different levels of system organization. Current models are based on observed rates of cancer mortality in atomic bomb survivors, extrapolating from high dose and dose rate to occupational doses and dose rates by means of a dose and dose-rate effectiveness factor (DDREF). While emphasis in the past has been on the risk of cancer, Figure 1.1 summarizes the much larger collection of risks and potential outcomes bearing on the health and performance of astronauts that need to be taken into account.

Although a detailed analysis of specific risks was beyond the scope of the workshop, the radiation protection community has established that at low doses and low dose rates, radiation exposure limits that adequately protect individuals from excessive increases in cancer rates also protect them from acute risks.

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[7] The GCR heavy ions, which contribute most of the dose equivalent, have nuclear collision mean free paths and ranges that are significantly less than those of the high-energy protons. Since the stopping power (linear energy transfer [LET]) increases with the Z^2 of the particle, the ranges of most of the ions below several hundred MeV are less than or comparable to their nuclear collision mean free paths, and certainly much, much less than 100 g/cm^2. At higher energies the ranges are only ~2 to 3 times the collision mean free paths. For example, the range of a 1 GeV per nucleon Fe ion is ~27 g/cm^2 in water. Its nuclear collision mean free path in water is ~15 g/cm^2. When the Fe breaks up (fragments), the secondaries have lower Zs and hence lower LET and smaller dose and dose equivalent contributions, even though the particle numbers increase. Thus, when the entire GCR spectrum is considered, the dose equivalent is reduced as the incident spectrum and its secondaries propagate through the shield.

Radiation Risks

- Carcinogenesis
  - ☐ Leukemia
  - ☐ Solid Cancers
- Degenerative Tissue Effects
  - ☐ Heart Disease
  - ☐ Cataracts
  - ☐ Respiratory Disease
  - ☐ Digestive Diseases
- Damage to the Central Nervous System
  - ☐ Motor Skills
  - ☐ Behavior
  - ☐ Accelerated Aging
- Acute Risks
  - ☐ Death
  - ☐ Vomiting/Nausea

Potential Outcomes

- Mortality: Reduced Life Span
- Mortality: In-flight (Acute from SEP Events)
- Performance Degradation
- Morbidity: Post-Flight

FIGURE 1.1 Summary of radiation risks to humans on exploration missions.

Degenerative tissue effects and damage to the central nervous system have not been detected at doses of low LET radiation that are considered acceptable with respect to cancer risk. However, there is some basis for concern that the HZE component of the space radiation environment may produce unique damage leading to degenerative tissue effects and/or central nervous system damage. This question is the subject of ongoing research using simulated galactic cosmic ray irradiation (see Box 1.2, "The NASA Space Radiation Program"). Acute effects of radiation are a concern at relatively high doses delivered at high dose rate. Consequently, they are a potential risk of solar particle events. Acute effects are also of concern in some

BOX 1.2
THE NASA SPACE RADIATION PROGRAM

NASA is required by law to set limits on human radiation exposure in space and to implement appropriate risk mitigation measures. Currently, NASA has an ongoing, multidisciplinary radiation program involving research in radiation biology and physics to implement these obligations. In addition, there is an established operational program at NASA—the Space Radiation Analysis Group, or SRAG—that integrates information on the radiation environment, radiobiological assessments, mission radiation measurements, and flight rules. Engineering methods are also under development by NASA-funded researchers to evaluate the performance of materials and devices exposed to radiation.

The NASA program is intended to achieve three main goals: (1) to predict all significant health effects arising out of exposure to space radiation, (2) to reduce the uncertainty in risk predictions by acquiring essential biological knowledge leading to accurate models of risk assessment, and (3) to develop risk mitigation technologies. The program is based on the fact that only ground-based simulation of space radiation can yield statistically significant results for realistic experiments in a timely manner and at a cost far below that associated with space-based experiments. The role of space-based measurements is reserved for experiments able to provide statistically significant validation of sensitive model predictions and for radiation measurements not accessible to Earth experimentation (e.g., the neutron albedo of Mars).

Accordingly, NASA has signed agreements with the U.S. Department of Energy leading to the construction, commissioning, and ongoing operation of the NASA Space Radiation Laboratory at the Brookhaven National Laboratory in Upton (Long Island), New York. This facility provides beams of charged particles ranging from protons to gold, at energies between 0.1 and 3,000 GeV per nucleon. The beams used generally consist of a single particle at a single energy, but mixed beams and multi-energy beams can be delivered, for example, to simulate the solar particle event spectrum of protons or the distribution of galactic cosmic rays.

Beam-time proposals are reviewed by a Brookhaven/NASA science advisory committee with physics, biology, and engineering members to ensure compatibility between experiments, proper infrastructure support, and appropriate experiment design. Beam-time use by peer-reviewed program investigators is paid for by NASA, as is occasional use to gather preliminary data, noninterfering "piggyback" experiments, and peer-reviewed research funded by other NASA programs or other government agencies, subject to Memoranda of Agreement. Separate funding is required for recurrent use, at a level depending on beam use and long-term requirements.

NASA's space radiation program has strong communication with other elements of the NASA radiation protection community. In particular, it provides risk estimates to SRAG and other mission planners.

medical applications or radiation, particularly in cancer therapy, and have been extensively studied in that context. Generally, studies have been limited to low LET radiation, although some data are available from accidental exposures to neutrons, which result in higher LET ionizing particles.

Currently, career exposure to radiation is limited so as to lead to less than a 3 percent increase in lifetime fatal cancer risk (excess relative risk, or ERR) relative to the average cancer mortality risk of the entire population (approximately 20 percent). These allowable risks are determined using estimates made by the National Council on Radiation Protection and Measurements (NCRP) of age- and gender-dependent risks as a function of radiation dose. NASA will ensure that this risk limit is not exceeded at a 95 percent confidence level using a statistical assessment of the uncertainties in the risk projection to limit the cumulative weighted dose (dose equivalent in units of sievert) received by an astronaut throughout his or her career.[8] Based on the physical characteristics of space radiation, current practice uses the product of dose and a tabulated quality factor (Q) to calculate the dose equivalent (in units of sievert) as the quantity best related to risk. On this basis, radiation limits are established to ensure that the limiting health risks are not exceeded.

The values of Q in current use were selected to represent the risks of radiations, such as neutrons and alpha particles from radioisotopes, delivered at low dose rate, that may be encountered in terrestrial activities. One of the recognized sources of uncertainty in risk estimates is the applicability of these values of Q, based on the stopping power of the radiation, for HZE particles. High-velocity heavy particles and lower-velocity lighter particles can have the same stopping power (and therefore the same Q), but the energy deposited in individual biological cells and the number of cells affected by these particles can be quite different. Studies with cultured mammalian cells and particles from high-energy accelerators often show that the biological effects of different particles with the same stopping power are not exactly the same. The significance of these results in terms of health risks to organisms is still unknown. However, the relationship between health risk and stopping power or other properties of the directly ionizing particles is critical for predicting risk in space, because the interactions of GCR particles with spacecraft components, shielding, and tissue result in the production of nuclear fragmentation products that have charge, velocity, and stopping power different from those of the primary particles. The physical properties of these fragmentation products depend, in part, on the atomic structure of the materials of the spacecraft. If one is using an inaccurate relationship between the physical properties of the fragmentation products and the biological risk they produce, the effectiveness of different shielding materials in terms of risk reduction might be misjudged. Although this contribution to uncertainty in risk estimates was well known among workshop participants, it was beyond the scope of the workshop, and discussion was generally limited to issues with respect to an accurate determination of Q based on its current definition.

Another source of uncertainty is the effect of dose rate that depends both on the biological endpoint (the risks in Figure 1.1) and the physical properties of the radiation. For HZE radiation, carcinogenesis may be nearly independent of dose rate, while acute risks depend very strongly on dose rate. Consequently, the risk due to acute effects depends strongly on the magnitude of solar particle events, while the risk due to carcinogenesis depends on the total dose equivalent. The estimate of which risk dominates may depend on the timing of the mission relative to the solar cycle.

The legal and practical requirements of maintaining occupational radiation safety include the establishment of criteria to keep radiation exposure *as low as reasonably achievable* (also known as the ALARA principle). Good radiation protection practice thus involves setting up a margin of safety. At NASA, that margin of safety has been defined as the level of radiation exposure that will result in an estimated risk below the limit at the 95 percent confidence level. The overwhelming contribution to these uncertainties comes in the biological area, owing to the lack of knowledge regarding the effects of protracted exposure, the values of suitable quality factors as a function of the stopping power for the HZE particles and neutrons, and the suitability of extrapolation from the biological systems used in the laboratory to the human situation. This is true as well for risks other than cancer risks. For this reason, the radiation research requirements are preponderantly focused on radiobiological uncertainties. Physical sources of uncertainty contribute to

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[8] The sievert is the unit of dose equivalent (symbol H), which is related to biological risk from an absorbed dose (symbol D). A gray is the unit of absorbed dose, which is the mean energy imparted (absorbed) per unit of mass in the target material (e.g., tissue) (1 gray = 1 joule per kilogram). By definition $H = QD$, where Q, the quality factor, is a weighting factor that accounts for the biological effectiveness of the charged particles producing the absorbed dose.

risk estimates but are mainly of importance in operational considerations. Radiation limits (i.e., standards) have not been established for missions planned in the VSE. The Earth-orbital standard (i.e., 3 percent probability of mortality) is often used as an example when determining whether estimated Mars mission risks fall above or below it for various mission scenarios.

The large uncertainties that exist at present increase the cost of missions owing to the large safety margins required as a consequence, and they also limit the ability to judge risk mitigation methods, such as improvements in shielding or biological countermeasure effectiveness. Operational measures and radiation shielding are currently the main means of reducing radiation risk; improved biological markers have the potential to enable improved early diagnostics; the discovery of means of biological prevention and intervention may lead to significantly more powerful methods to overcome the biological consequence of exposure to radiation, including better radioprotectants.

Ultimately, the establishment of limits is complicated by several factors. Among these is that scientists cannot predict all the significant risks: radiation as the cause of some health effects, especially at moderate doses, is only conjectured; the time-dependence of some clear risks is not well known—for example, the appearance of cataracts many years earlier than normally expected; and the correlation of radiation with genetic (i.e., hereditary) and environmental (e.g., microgravitational) factors is known poorly or not at all. In addition, there is substantial uncertainty in the risks that can be predicted, so that predictions for a Mars mission may be too small or too large by a factor of two to three. As a consequence, the number of *safe* days on mission (i.e., the mission duration for which a crew member will not exceed risk limits within a 95 percent confidence interval) is currently less than three 180 day International Space Station missions and less than a 1,000 day Mars mission.

Biological knowledge is insufficient for the design of practical prevention and intervention methods, and reliable biomarkers predicting individual radiation risk are not available. The existence of only limited data on nuclear interactions of space radiation with matter and the limitations in models of radiation transport in matter contribute to these uncertainties and restrict the development of methods to optimize the distribution of spacecraft materials for optimal shielding configurations (the so-called multifunctional use of materials for designated spacecraft functions that simultaneously have optimal shielding properties, e.g., certain plastics relative to standard metal components).

As a consequence of these limitations, the number of days that a crew member can spend in space (including on multiple short missions) without exceeding the radiation standard established for Earth-orbital missions at the 95 percent confidence level is considerably less than the number of days required for missions within the Vision for Space Exploration (see Table 1.1). Note from Table 1.1 that 10 g/cm^2 aluminum shielding is clearly inadequate for a Mars mission.

TABLE 1.1 Projections of Age- and Gender-Dependent Maximum Mission Days in Deep Space for a 95 Percent Confidence Level to Stay Below a 3 Percent Excess Fatal Cancer Probability

Age	For Females (No. of Days)	For Males (No. of Days)
30	54	91
35	62	104
40	73	122
45	89	148
50	115	191
55	159	268

NOTES: Body self-shielding and 10 g/cm^2 aluminum shielding were assumed. Calculations were made near solar minimum where highest galactic cosmic radiation exposures occur.
SOURCE: Adapted from Cucinotta et al. (2001; 2006, in press).

HARDWARE RISKS

Solar activity can affect instrumentation, spacecraft subsystems, and communications in several ways. Among the space environment effects that are of concern for instruments, spacecraft, and communications are the following: single-event effects in electronics and sensors, the total radiation dose to components, radiation damage to sensors and solar cells, and electrostatic charging.

Solar energetic particle radiation degrades the performance of solar cells. This radiation may also affect electronics in all types of instrumentation and can also interfere with all kinds of sensors, both by direct ionization and by the activation of the sensor or surrounding materials. Direct ionization can interfere with the imagery obtained using charge-coupled-device (CCD) cameras and may degrade optical and thermal control surfaces. Activation can interfere with gamma ray spectrometers used for scientific investigations. All of these effects are of concern for missions to the Moon and Mars.

As shown in Figure 1.2, single-event upsets occur in microelectronics when an individual charged particle, usually a heavy ion, deposits enough charge at a sensitive portion of the circuit to cause that circuit to change state. The physical size of the electronics element tends to determine the sensitivity as well as the probability that a single-event upset will occur.

Not only are galactic cosmic rays (specifically the heavy-ion component) important in causing space environment effects on hardware, but protons and heavy ions from solar particle events or in the trapped radiation belts (especially in Earth's South Atlantic Anomaly region) can cause significant problems during critical phases of space missions. The heavy ions in Earth's radiation belts can often be handled by mass shielding. However, many times it is nearly impossible to shield against very energetic cosmic heavy ions. The complexity of the space environment makes solutions to some solar event upset problems difficult. However, there often are workable and effective hardware and software solutions.

Large disturbances on the Sun's surface have long been known to accelerate very energetic particles and also often give rise to strong traveling shock waves in the interplanetary medium. Given a proper IMF connection between the disturbance site on the Sun and a spacecraft, very energetic solar protons can begin reaching satellite environs within tens of minutes and peak in a matter of hours. These very energetic protons can cause very prompt effects on hardware. A more delayed effect results from the shock waves often produced in the solar wind by coronal mass ejections. Since radial propagation speeds are normally ≤1,000 km/s for these disturbances, it takes 1.5 to 2 days for a shock wave to reach 1 AU.

It has also been demonstrated (e.g., Reagan et al., 1983; Vampola, 1987) that irradiance of space systems by very energetic electrons can cause deep-dielectric charging. In this process, very high energy (i.e., very penetrating) electrons bury themselves in dielectric materials (e.g., coaxial cables and other insulators). These electrons then give rise to high electric fields (potential differences of several kilovolts) in their vicinities until eventually an intense breakdown occurs (see Figure 1.2). In many cases an irrefutable correlation of spacecraft anomalies with the high-energy electron environment exists, and the plausible physical charging relationship is well established (Baker, 2004).

A significant effect of lower-energy particle bombardment (from the standpoint of space operations) is the occurrence of spacecraft surface charging (see Baker, 2004). During a surface-charging event, insulated regions on a spacecraft may charge to several kilovolts potential (usually negative relative to the ambient potential). This charging occurs because of a lack of current balance between the local plasma medium and the spacecraft surface (as illustrated in Figure 1.2). When a spacecraft is immersed in a cool, dense plasma, the incident particles (electrons and ions), as well as secondary emitted particles, photoelectrons, and backscattered electrons, all balance. This gives a low net spacecraft potential. However, in a very hot, tenuous plasma, current balance can be difficult to achieve, and large potentials can build up.

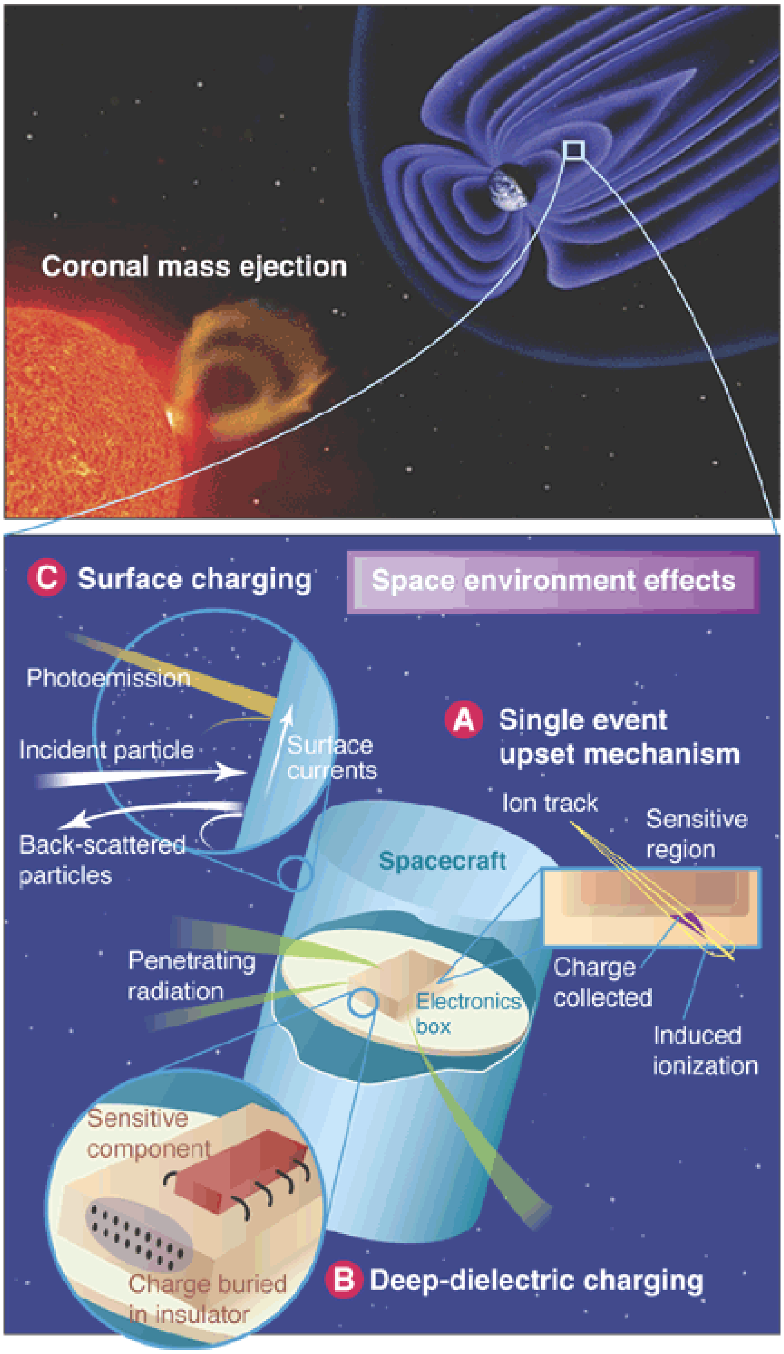

FIGURE 1.2 Space weather and its effects. (Top) The connected Sun-Earth system. A large coronal mass ejection propagates from the Sun toward Earth and its magnetosphere. (Bottom) Space-weather-induced effects on an Earth-orbiting spacecraft: (A) single-event upsets due to energetic ions, (B) deep-dielectric charging due to relativistic electrons, and (C) surface charging due to moderate-energy electrons. SOURCE: Reprinted with permission from Baker, 2002. Illustration: Preston Morrighan. Copyright 2002, American Association for the Advancement of Science.

From an operational standpoint, differential charging of satellite surfaces can lead to significant discharges. Discharges introduce noise into subsystems and may interrupt normal spacecraft operations or represent a false command. In the process of discharge breakdown, physical damage may occur. This may change the physical characteristics (thermal properties, conductivity, optical parameters, and so on) of the spacecraft. Furthermore, the release of material from the discharge site has been suggested as a contamination source for the remainder of the vehicle (see Baker, 2004, and references therein).

Instruments and equipment that will be used on missions to the Moon and Mars need to be tested for their suitability and robustness in a variety of space environments. These environments include diverse regimes that range from conditions near Earth to interplanetary space, to the Moon and Mars. If commercial off-the-shelf parts and systems such as personal computers and videocameras are used heavily, they will need testing to ensure performance in the disparate environments. This will require access to adequate high-energy particle beams at accelerators for testing and related performance measurements to simulate the space radiation environment under controlled conditions.

Space environment modeling plays a vital enabling role for missions to the Moon and Mars. At Earth, static trapped radiation belt models such as AE8 and AP8 that predict electron and proton flux spectra in Earth's radiation belts are inadequate and outdated. Even the more recent 1990s-era models based on data from the Combined Release and Radiation Effects Satellite are limited because they were based on a very brief interval (about 1 year of data). Updated models that are dynamic, taking into account current solar wind and magnetospheric conditions, are needed in order to provide the history of variations on timescales that range from solar cycle to minutes. If Mars mission architecture includes parking a transit vehicle at geosynchronous orbit, it will be necessary to understand the spacecraft charging environment better, including short-term variations at that location. More work is needed to gain an understanding of the most appropriate SEP models and methods that characterize these conditions, including extreme-event studies, risk-based models, and data-based analysis of long-term records. Improved models of proton and heavy-ion environments (flux, fluence, and energy spectra) in SEPs are needed because of their effects on systems.

Generally, the engineering approach is to harden systems against worst cases; however, the unexpected can always occur. In such circumstances, a number of actions can be taken in response to predictions of poor space weather. Sensors can be safed, noncritical systems can be shut down to prevent damage and latch-up, sensors can be oriented in a direction that is least susceptible to damage, increased attention can be given to monitoring operations and to the interpretation of sensor data, and mission activities can be limited during high-background events.

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2

Specifying and Predicting the Space Radiation Environment

The Sun clearly has many effects on Earth. The energetic radiations, mainly charged particles, that present a significant hazard for space exploration arise from magnetic processes in the solar atmosphere. These in turn have their origin farther down in the Sun's outer layers, where the magnetic field originates.

HELIOSPHERIC MAGNETIC FIELD

The Sun's surface rotates once every 27 days near its equator (and about 30 percent slower at the poles), which results in a clear 27 day cycle in many manifestations of solar activity at Earth. Solar activity is most often associated with solar active regions, which generally last for several solar rotations and that are localized regions on the solar surface where sunspots, flares, and other magnetically related phenomena occur.

The Sun's magnetic field and its associated activity exhibit a 22 year cycle—twice the familiar 11 year sunspot cycle, because the dominant polar magnetic fields have opposite polarities for consecutive 11 year sunspot cycles. The index of sunspots has an average period between successive maxima or minima of approximately 11 years, and the Sun's large-scale magnetic direction changes near each sunspot maximum to produce the total 22 year magnetic cycle. Again, many manifestations at Earth reflect this cyclic behavior.

The large-scale solar magnetic field has a clear dipolar structure (with significant smaller-scale variations) in the years around sunspot minimum, which reverses sign at sunspot maximum. Recent observations from the Ulysses spacecraft suggest that the field remains somewhat dipolar during the change in sign, with the dipole rotating to change its direction.

Helioseismological observations have led to a picture in which the origin of the Sun's magnetic field is a dynamo acting at the base of a region of convective overturning in the outer layers of the solar interior. Models of the dynamo suggest that the turbulent convection couples with solar rotation to produce the large-scale magnetic field. A full understanding of solar activity and its resulting radiations depends in part on an understanding of the dynamo mechanism. Scientific knowledge is still not yet complete enough to make short- or long-term predictions adequate to possibly predict the particle environment. At present, more-phenomenological models that use observations at the solar surface to make short-term predictions must be relied on.

GALACTIC COSMIC RAYS

The phenomenon of the solar modulation of cosmic rays is the result of the solar wind and its magnetic field inhibiting the interstellar cosmic rays from entering the inner solar system. Since the effect is at a maximum during high sunspot activity, the cosmic ray intensity is a minimum at Earth during the period around sunspot maximum. Conversely, it reaches a maximum at Earth during sunspot minimum. This reflects a general, heliospheric depression of the intensity of galactic cosmic rays, which are entering the solar system from the outside.

The heliosphere, the bubble with the Sun at its center, is carved out of the interstellar gas by the solar wind, which blows radially outward, carrying with it the solar magnetic field, producing a classical Archimedean spiral magnetic field. (See Figure 2.1.) At a radius of about 100 AU, because of the resistance of the interstellar gas, the wind undergoes a shock transition to subsonic flow. This shock is called the termination shock. Some distance (probably about 30 to 50 AU) beyond the shock is the contact surface that separates the ionized part of the interstellar gas from the solar wind gas. A possible second, outer shock in the interstellar plasma is also present. The outer portions of this picture, beyond the inner shock, are not well understood. Fortunately, the general properties of the modulated intensity of approximately

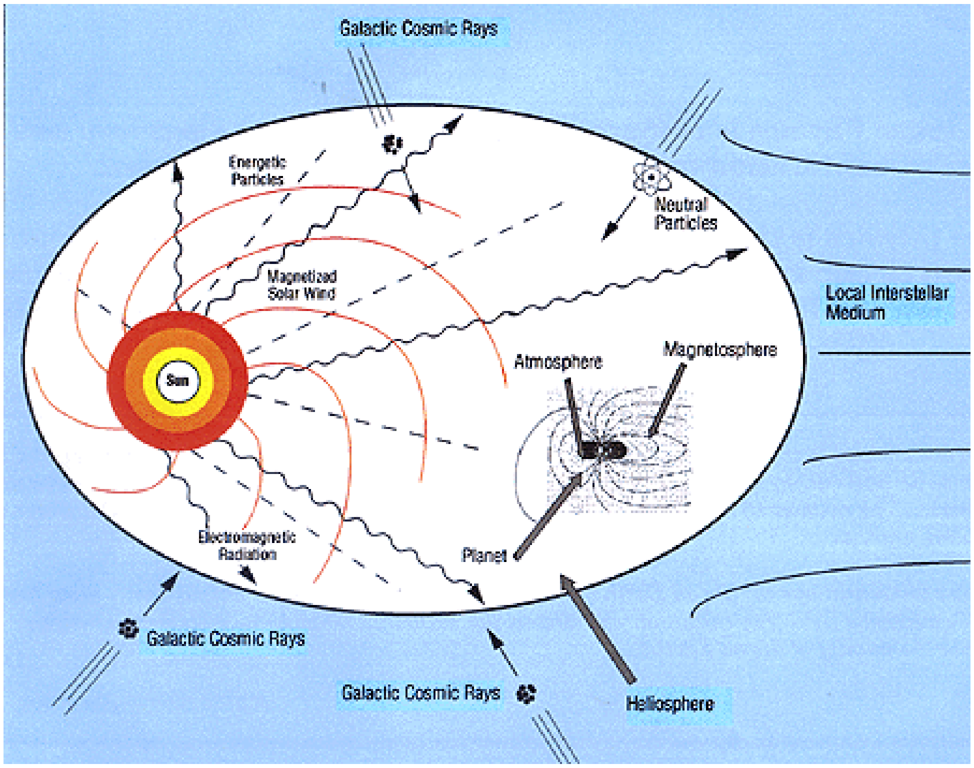

FIGURE 2.1 The heliosphere. SOURCE: Courtesy of National Aeronautics and Space Administration.

1 GeV particles are not sensitive to these uncertainties, and a reasonable quantitative understanding of the physics has been attained.

The heliosphere is bathed by an essentially isotropic, uniform distribution of galactic cosmic rays that is expected to remain steady over periods of thousands of years. These cosmic rays have difficulty in traveling into the inner solar system, resulting in a depressed intensity there. The problem is to understand this quantitatively in terms of what is known of the solar wind and cosmic ray transport. Since the solar wind is supersonic, the inner part of the heliospheric plasma and magnetic field are not affected much by the uncertainties at the outer boundary. The transport of the cosmic rays is determined by solar wind and its embedded magnetic field, both of which are convected out by the supersonic wind flow.

The large-scale structure of the magnetic field has been clarified considerably by observations carried out on the Pioneer, Voyager, and Ulysses spacecraft, and by the inferred relationship to observed coronal structure. During the years around each solar sunspot minimum, the field is generally organized into two hemispheres, separated by a thin current sheet at low heliographic latitude across which the field reverses direction. In each hemisphere the field is generally assumed to be the Archimedean spiral, with the sense of the field being outward in one hemisphere and inward in the other. At sunspot minimum, the current sheet is nearly equatorial. The structure for the years near sunspot maximum is not simple, with transient solar activity causing significant, large-scale propagating disturbances.

One other aspect of the theory of modulation and transport in the heliosphere is the study of the anomalous component of the cosmic rays, which are an important component at energies around a few hundred MeV. It appears that these particles are freshly ionized interstellar particles accelerated at the termination shock by the mechanism of diffusive shock acceleration.

The spacecraft Voyagers 1 and 2 are at present studying the outer parts of the heliosphere, and Voyager 1 has actually crossed the termination shock. This extended Voyager mission, to study the outer heliosphere, has provided important insights into the shape of the heliosphere and the mechanism of energetic particle acceleration. Other spacecraft, including Ulysses and the Advanced Composition Explorer (ACE), are observing the inner heliosphere.

To summarize the present knowledge, the modulation of galactic cosmic rays and the anomalous component are understood well enough to enable a confident prediction that the intensity will continue to vary in antiphase with the sunspot cycle, with variations of the order of 30 percent or so at GeV energies from sunspot minimum to sunspot maximum. It is possible that unexpected solar phenomena could produce lesser or larger effects.

SOLAR ENERGETIC PARTICLES

Energetic particles with energies occasionally exceeding several GeV are often produced in sporadic events at the Sun associated with solar activity. Solar flares and coronal mass ejections (CMEs) produce the energetic particles by processes whose specific nature is still being studied. The energy spectrum of the solar energetic particles is softer than that of galactic cosmic rays, and the events typically last for periods of hours to days. The intensities during the events can be quite large, although at energies above several hundred MeV, the time-integrated galactic cosmic ray flux is larger than that of solar cosmic rays. The events occur sporadically, although less frequently near sunspot minimum, and cannot be easily predicted. The basic energy source for the particles is the solar magnetic field, which becomes unstable and dissipates magnetic energy very rapidly, producing an explosive event. The explosion produces transient effects in the surrounding plasma, which then accelerates the solar energetic particles (SEPs). In addition to observations of the particles themselves, solar energetic particles produce variable electromagnetic radiations such as radio waves, x-rays, and gamma rays, which serve as remote diagnostics of the particle acceleration and transport.

Solar energetic particle events can be classified as gradual (lasting days) and prompt (lasting hours). The particles in gradual events are mainly accelerated by propagating shocks generated by CMEs that propagate from very near the Sun to beyond the orbit of Earth. The acceleration process at the CME shock is fundamentally the same as the process producing the anomalous cosmic rays at the heliospheric termination shock. The time profile and energies produced by this acceleration are defined by both the nature of the CME and the properties of the interplanetary medium through which the shock propagates. The details of this process are still being debated, and only the most basic properties are understood. Detailed predictions are still a long way off. The composition of these events indicates that the process of acceleration may involve the existence of “seed” particles (low-energy superthermal particles) that were accelerated earlier in prompt solar energetic particle events.

The prompt solar energetic events are much shorter in duration and are apparently directly related to an explosive event in the solar atmosphere. It is possible that the event produces turbulent fluctuations or waves in the ambient plasma and magnetic field, which then accelerate a fraction of the ambient ions and electrons to very high energies. Alternatively, the event could produce localized shock waves, which would then be expected to accelerate the particles by the process of diffusive shock acceleration, as do the propagating CME shocks and the heliospheric termination shock (Jones and Ellison, 1991). The transport processes, although understood in broad outline, still are not understood well enough to permit detailed predictions.

Methods involving artificial intelligence, Bayesian inference, and locally weighted regression have demonstrated promise in providing “nowcasting” capabilities after SEP event particles begin to arrive. These methods are capable of predicting, with reasonable accuracy, total doses and the future temporal evolution of the dose as particles arrive very early in the evolution of the event. However, these methods are at present unable to forecast SEP event fluence levels and their associated doses until after particles begin to arrive. Hence, they could provide a much-needed short-term capability for mission operations, but in a merely stopgap role. Computer codes implementing these models are currently research codes and not in the form of operational tools that are usable by mission operations personnel (see the report of Working Group E in Appendix A of this report).

Current SEP event forecasting models are climatological and empirically based and trigger on flare electromagnetic emission. Predictions from the National Oceanic and Atmospheric Administration (NOAA) use x-rays; the U.S. Air Force (USAF) uses microwaves or x-rays; both use optical position of active region. NOAA predicts onset, duration, and peak flux, while the USAF predicts time, intensity, and spectra (assumes 404 km/s solar wind and Archimedes spiral). NOAA supports the NASA Space Radiation Analysis Group (SRAG) via Geostationary Operational Environmental Satellite (GOES) measurements. NASA then takes GOES data and predicts doses inside the International Space Station (ISS). For the average well-connected event, these methods predict the maximum intensity within an order of magnitude and the timing of the maximum within a couple of hours. These methods, however, fall apart for shock-dominated events. Hence, *current forecasting models do badly in predicting extreme events, and extreme events represent the greatest danger to human spaceflight crews.* The consensus of the workshop’s relevant task group (see the report of Working Group C in Appendix A) on current models is that known physics is not included in current models and needs to be added to them. Exactly how to do so is not clear at the present time, but major improvements to a predictive capability can be made if the physics-based models can incorporate measurements at the solar energetic particle source regions in order to pin down crucial model parameters that are currently missing. A large SEP event is illustrated in Figure 2.2.

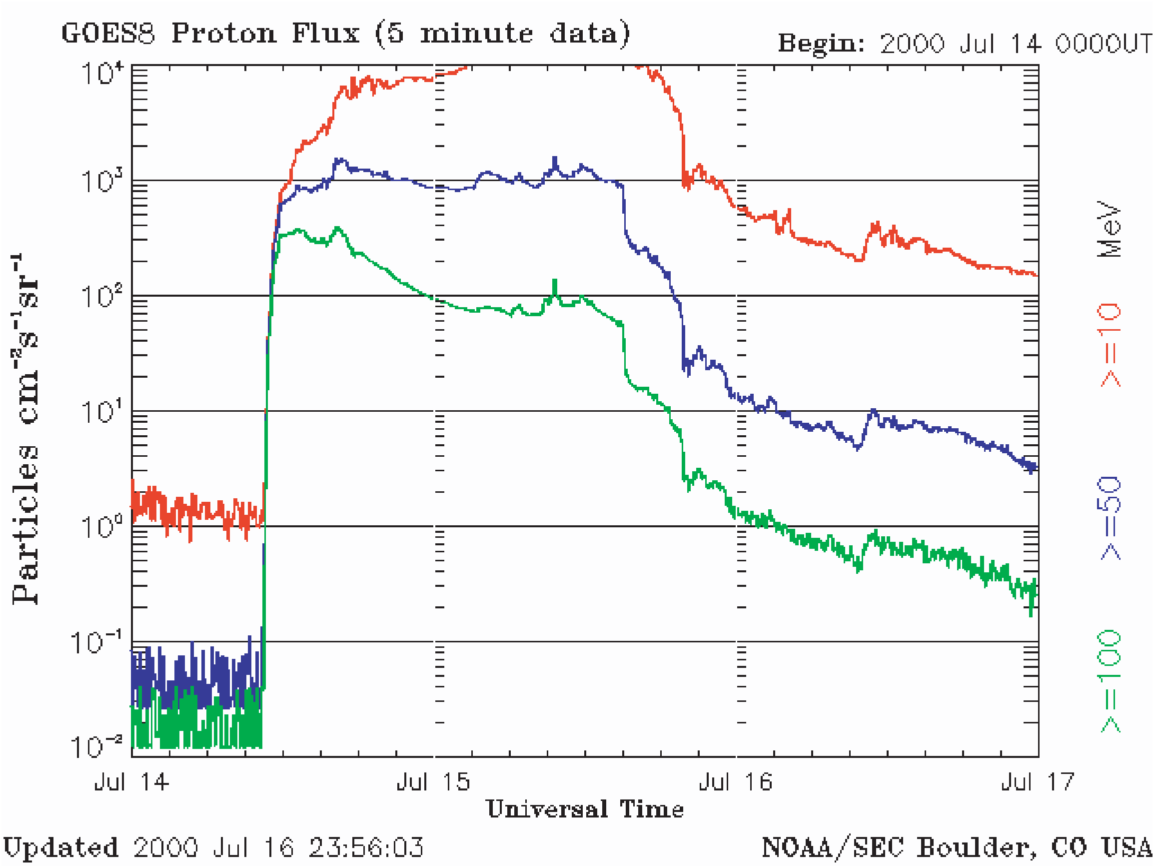

FIGURE 2.2 Proton fluence rate versus time for the large solar energetic particle event of July 2000. SOURCE: Courtesy of the National Oceanic and Atmospheric Administration Space Environment Center, Boulder, Colo.

Coronal Mass Ejections

Coronal mass ejections consist of large, balloon-shaped clouds of solar plasma and magnetic field that contain up to 10^{16} grams of matter and reach speeds in excess of 2,500 km/s. The kinetic energy alone is sufficient to boil the North Atlantic Ocean. CMEs are associated with solar flares and solar energetic particle events and occur most often during sunspot maximum. Most of the energy in such events is associated with the CME and not the flare. Such a cloud of gas drives a large-scale "bow" shock wave, which precedes the spheroidal cloud through interplanetary space and that accelerates the energetic particles in gradual solar energetic particle events. When this shock wave and cloud strike Earth's magnetosphere, there are usually significant geomagnetic and ionospheric effects.

In white light images, CMEs often appear to have a bright, leading, looplike structure within which exists a dark cavity and a core of denser material—suggesting the eruption of a pre-event prominence, its overlying coronal cavity, and the ambient corona. The energy is thought to come from magnetic rearrangement (reconnection) near the base of a coronal loop, triggered by motions of the footpoints (the point where the field lines enter the Sun) of the magnetic field lower in the solar atmosphere. Thus, the energy ultimately comes from the conversion of magnetic-field energy to thermal and kinetic energy. It is further observed that CMEs tend to arise in coronal streamers in an equatorial belt that encircles the Sun. Knowledge of CMEs has advanced to the point of attempting to understand the trigger mechanism, which causes the sudden instability leading to the magnetic rearrangement after a relatively slow buildup of stresses. The processes leading to the buildup of stress are at present very poorly understood; hence, the basic causes of CMEs are still not known in any detail, so prediction is difficult.

Figure 2.3 shows the structure of a CME and the sources of particle radiation. Figure 2.4 is a Solar and Heliospheric Observatory (SOHO) image that illustrates the production of particles and also their effects on spacecraft sensors.

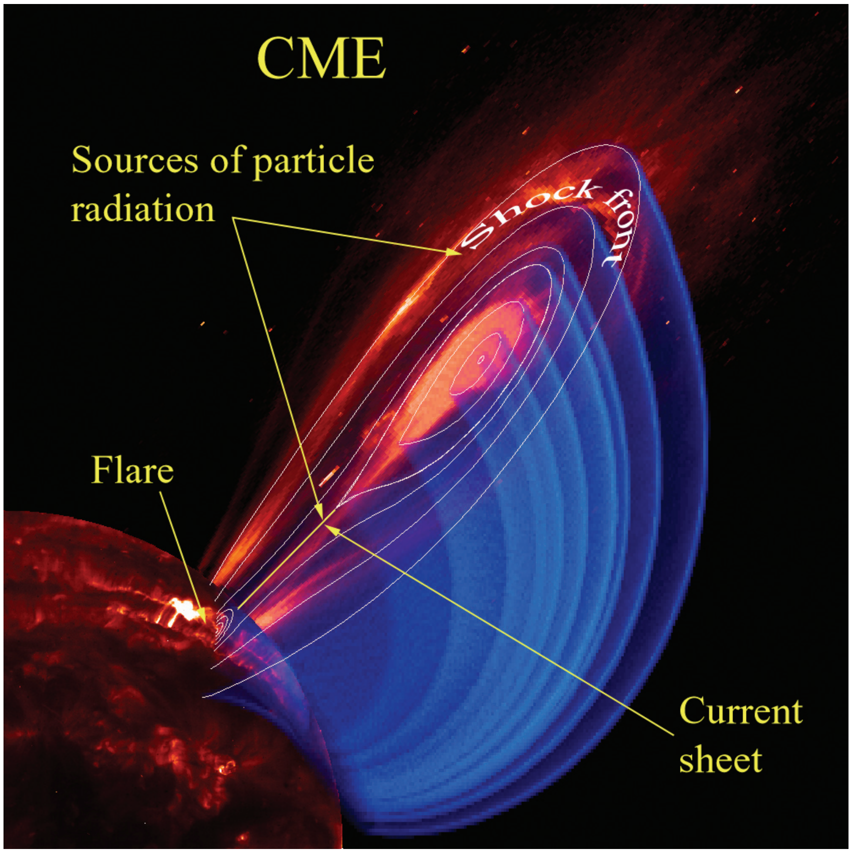

FIGURE 2.3 Composite illustration of a generic coronal mass ejection (CME) and flare system related to the production of energetic particles. Solar energetic particles are likely produced from the flare and current sheet and from the shock front near the leading edge in fast CMEs. The disk and coronal images (in red) were obtained from the Solar and Heliospheric Observatory Extreme ultraviolet Imaging Telescope and Large Angle and Spectrometric Coronagraph Experiment, respectively. The blue overlay shows a cutaway of the magnetic loops being expelled with the CME. SOURCE: Adapted from Kohl et al., 2006. Copyright 2006, Springer. Reproduced with permission of Springer Science and Business Media.

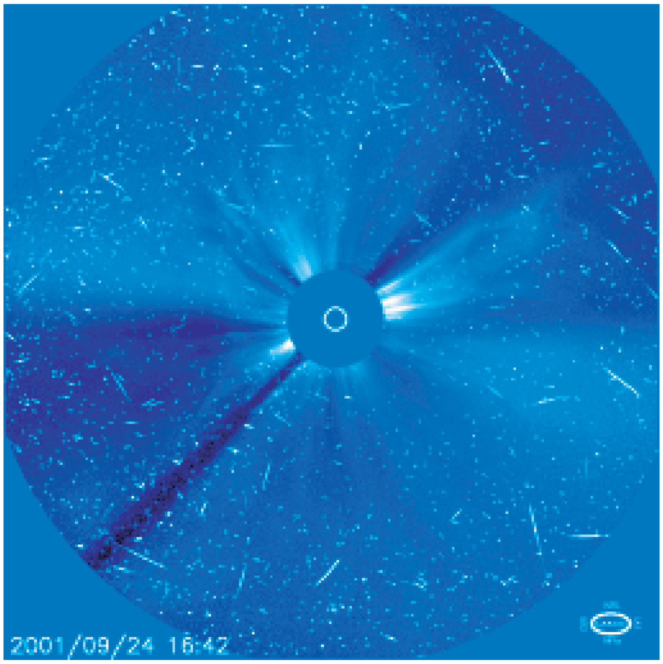

FIGURE 2.4 Image of a coronal mass ejection (CME) from the Sun, taken by the Solar and Heliospheric Observatory spacecraft, showing the source of particles and how they affect electronic equipment on a spacecraft. The image was taken after the eruption had passed Earth. The streaks (snow) in the image are caused by solar energetic particles, associated with the CME, striking the detector. SOURCE: National Aeronautics and Space Administration.

Flares and Active Regions

Flares occur during the rapid conversion of energy from the solar magnetic field to the kinetic energy of particles in localized regions at the base of the solar corona. The accelerated particles and their interactions with the surrounding plasmas and fields can also produce electromagnetic emission in a broad range of frequencies, from microwaves to gamma rays. Flares are one of the primary sites for the acceleration of electrons (up to 10 MeV) and protons and heavy ions (up to >100 MeV per nucleon), but the exact nature of the acceleration and their propagation out to the heliosphere is still being investigated. Flare-produced SEPs are of great concern because of their fast arrival times at Earth. In some cases, it takes just minutes for relativistic particles to travel along magnetic-field lines that connect directly to the source regions.

Flares have traditionally been associated with sources of SEPs, although whether they are a source distinct from the CMEs is still controversial (see, e.g., Gosling, 1993). It is very likely that flares and CMEs are different aspects of the same general phenomenon of magnetic reconnection on the Sun (Harrison, 1995). Long-duration flares (with x-ray emission lasting hours to days) have been associated with CME shocks that produce the largest, most energetic SEP events, whereas the impulsive x-ray flares with relatively short rise times and durations (seconds to hours) produce the less energetic SEPs. A glaring exception to this tendency is the January 20, 2005, SEP event that produced one of the most energetic particle events ever recorded, although it has many of the characteristics of an impulsive, fast rise time flare event (see Simnett, 2006). One possibility is that large SEP events may involve both flares and CME shocks. The flare may provide the suprathermal seed particles that are then processed in the CME shock.

Active regions are places where the Sun's magnetic fields are changing rapidly owing to flux emergence or cancellation. The study of these regions is important in the context of predicting where flares are most likely to occur on the Sun. Decades of observations of active regions show that magnetic-field configurations that are highly sheared tend to produce the most flares. Determining which of these flares will produce large SEP fluxes would be of extreme importance for the prediction of the radiation environment in the heliosphere.

PROSPECTS FOR LONG- AND SHORT-TERM FORECAST MODELS

On the basis of current knowledge and present progress, participants at the workshop expressed optimism that solar and space physics researchers will be able to specify the space radiation environment accurately and will be able to forecast both long-term trends and short-term events. However, the success of such a specification and prediction program will require a careful and continuing effort to be conducted by the research programs of NASA and NOAA (and other agencies).

Long-Term Forecasts (Years to Decades)

It is well known that sunspot number is correlated with various measures of solar activity, including sunspot area, 10.7 cm radio flux, x-ray flares, total irradiance, the geomagnetic aa index, and cosmic ray flux. There have been successful empirical predictions of the peak of a solar cycle using sunspot trends in the earliest years of that cycle. In spite of these partial successes, accurate, long-term predictions of the solar-cycle properties and the physics underlying solar-cycle variability remain a major challenge in solar physics.

A promising approach that was presented at the workshop and subsequently published (for instance, in Dikpati et al., 2006) appears to have substantial predictive capabilities. This approach relates to dynamo models that incorporate meridional flow throughout the convection zone to transport magnetic flux (so-called flux-transport models) toward the poles at the surface and toward the equator near the convection zone base (see Figure 2.5). This approach may be very useful, but remains controversial.

A current flux-transport model correctly simulates the relative peaks of the past 8 solar cycles, and predicts that cycle 24, beginning in late 2006 or early 2007, will be 1.3 to 1.5 times the amplitude of cycle 23. This prediction is in contrast to recent predictions made using so-called precursor methods (Svalgaard et al., 2005; Schatten, 2005). It has been acknowledged that precursor methods have uncertainty that reduces as the cycle approaches closer to its peak. By contrast, flux-transport dynamo-model-based predictions use the Sun's magnetic memory, whose duration is controlled by the meridional circulation and magnetic diffusion. This class of solar dynamo model may also have considerable success in predicting cycle amplitude 2 cycles ahead and therefore may be able to predict the amplitude of cycles 20 to 25 years in the future (Figure 2.6).

The latitudinal speed of movement of sunspot appearance toward the equator as the solar cycle advances is anticorrelated with sunspot-cycle period (Hathaway et al., 2003). That is, the faster the drift rate the shorter the period. Flux-transport dynamo models show similar behavior. The equatorward drift velocity of a cycle is correlated with the amplitude of the second following cycle. This property is also seen in flux-transport dynamos with deep meridional circulation. This fact supports the possibility of predicting cycle amplitudes two cycles ahead.

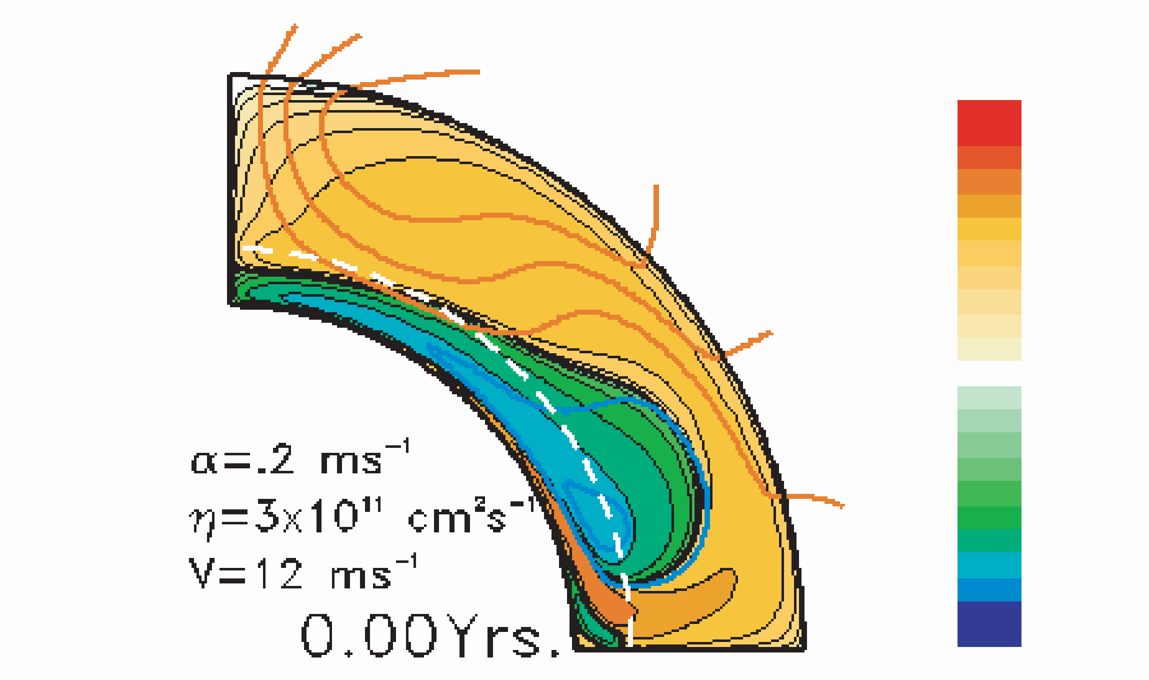

FIGURE 2.5 Dynamo models that incorporate a deep meridional flow to transport magnetic flux toward the equator at the base of the convection zone have predictive capabilities. SOURCE: Dikpati and Charbonneau, 1999. Reproduced by permission of the American Astronomical Society.

Short-Term Forecasts (Nowcasts to Days and Weeks)

Current models are inadequate to predict with confidence the onset or severity of a solar radiation event. These models typically describe separate parts of the problem (the flare or CME initiation, heliospheric propagation, interactions with planetary magnetospheres and atmospheres), but the latest models are now capable of describing the complete end-to-end system using various simplifications in their details.

Active regions contain complex magnetic structures that often erupt to produce flares and CMEs. While models exist that describe the magnetic-field evolution leading up to the eruption, the timing of the eruption is not yet predictable with these models. One method for predicting the probability of eruption is to identify S-shaped magnetic-field structures, called sigmoids, which are observed in x-ray and extreme ultraviolet (EUV) images of the corona (Canfield et al., 1999). The twisted configurations are thought to be related to the amount of magnetic helicity in the magnetic field. While the method is somewhat successful in correlating sigmoidal shape to active region eruptions, there are also nonsigmoidal active regions that can lead to eruptions but which are not predicted. Thus, this method needs improvement before it can be used reliably.

Other tools for predicting active region eruptions use photospheric magnetograms to determine the degree of nonpotentiality (overall twist and shear) and the amount of free energy in coronal magnetic fields (e.g., Falconer et al., 2003; Beveridge and Longcope, 2006). These research models are promising as future

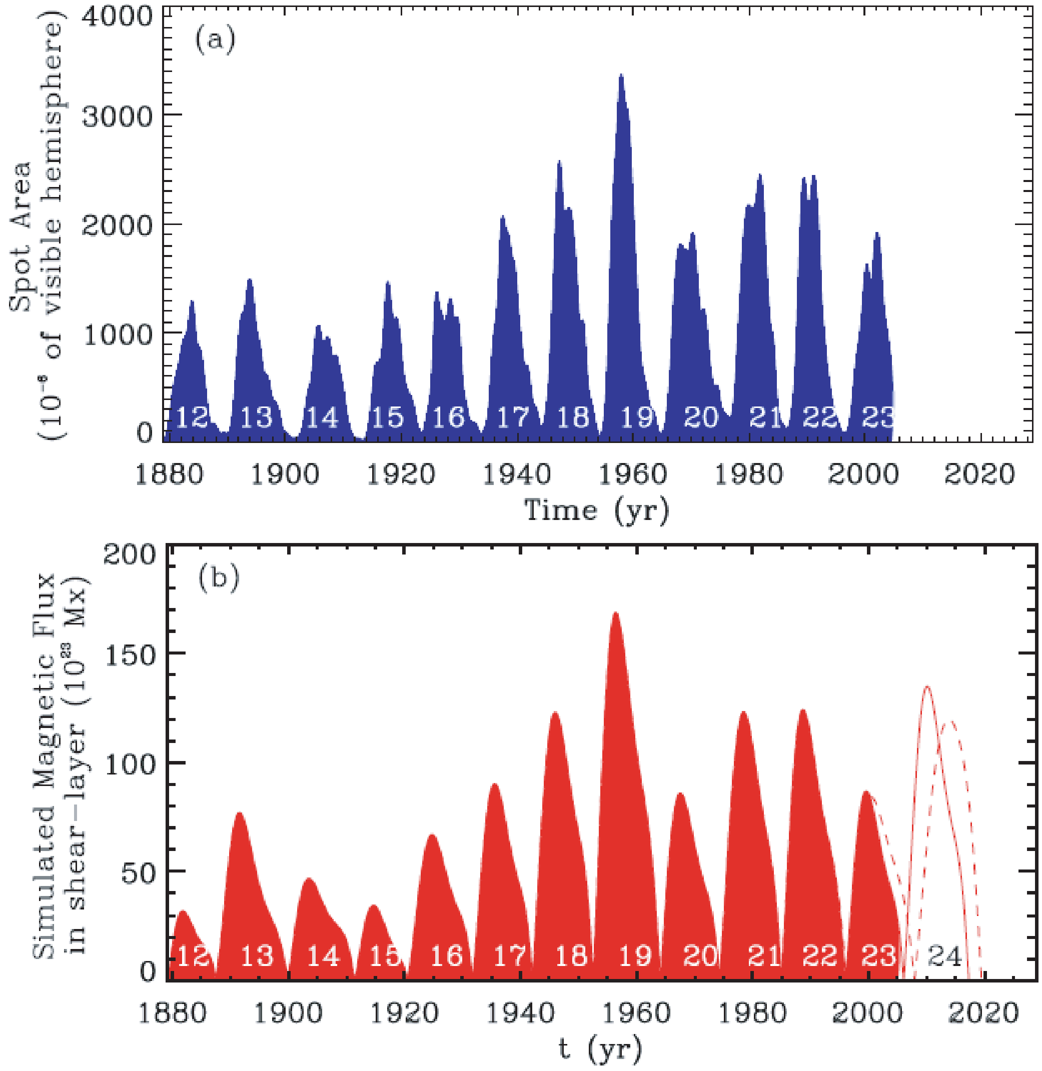

FIGURE 2.6 (a) Observed spot area (smoothed by Gaussian running average over 13 rotations) plotted as function of time. (b) Simulated toroidal magnetic flux in the overshoot tachocline within midlatitudes for the case with a steady meridional flow (solid red area and curve) and with the time-varying flow incorporated since 1996 (dashed red curve). SOURCE: Courtesy of M. Dikpati, University Corporation for Atmospheric Research.

forecasting tools because they include much of the relevant physics. All of the above methods require the active regions to be on the disk before making assessments.

The possibility for longer-term predictions may come from helioseismological models of active region formation beneath the photosphere, before their appearance on the surface (Braun and Lindsey, 2000). Helioseismology is also being used to track active regions while they are on the back side of the Sun (Braun and Lindsey, 2001). Currently, back-side tracking can only follow the largest sunspot groups, and the technique is not yet powerful enough to detect individual sunspots. However, the largest sunspots also tend to produce the biggest events. The most useful input data for forecasting active region eruptions are coronal vector magnetograms (not yet available), x-ray and EUV images, and helioseismological measurements.

Solar Wind and Heliospheric Models

Solar energetic particles propagate through the background solar wind and interplanetary magnetic field. Reliable predictions of SEP onset and severity cannot be made without understanding the heliospheric environment through which these particles propagate. In this regard, several groups are developing large-scale models to predict the plasma and magnetic-field environment of the global heliosphere. The NOAA Wang-Sheeley-Arge model (Arge and Pizzo, 2000) is an empirical model for forecasting solar wind speeds based on measurements of photospheric fields to obtain flux tube expansion factors. The derived values for flux tube expansion at the Sun are inversely related to solar wind speeds at 1 AU. More sophisticated three-dimensional magnetohydrodynamic models (e.g., Riley et al., 2001; Roussev et al., 2003) can now map velocity and magnetic-field structures in the heliosphere to specific structures in the solar corona. Such models can reproduce the large-scale features of the solar wind from solar magnetogram data and initial estimates of the density, temperatures, and velocities at the coronal base. These models are typically run until a steady-state solution is achieved. These magnetohydrodynamic models can be improved with more frequent magnetographic observations (typically, magnetograms are averaged over a solar rotation). Also, model validation can be improved with a more complete data coverage from remote sensing and in situ observations. These numerical models have not yet reached the stage of being able to routinely and reliably forecast solar wind conditions at Earth and other locations, and a major challenge for the models is to specify the north-south component of the interplanetary magnetic field that controls energy transfer at, for example, Earth's magnetopause.

Models for Coronal Mass Ejections and Flares and for Solar Energetic Particles

CMEs and flares are the primary sources of solar energetic particles, so understanding their onset and evolution are active areas of research. Predicting the onset of CME and flare eruptions is not possible with any high degree of accuracy with present models. However, statistical methods can be used for certain cases, such as well-connected energetic electron events, which can be used to specify CME launch times. Once an eruption has occurred, it is not yet possible to predict the properties of the SEPs produced, for example, the event duration, maximum flux, energy spectrum, and so on. Some models do better than others in predicting certain aspects of SEP events: for example, models by Zank et al. (2000) can produce the observed "spectral breaks" in the energy spectrum of shock-produced SEPs (integrated over the transit time from the Sun to 1 AU). The spectral break may be an indication of the energy for which particles escape from the shock. The Solar Particle Engineering Code (SOLPENCO) model (Aran et al., 2006) is able to predict qualitatively the proton flux and fluence time profiles for a broad range of heliolongitudes—from the west limb (W90) to a far eastern location (E75), but the model relies on average parameter values from a large number of SEP test cases. In general, the SEP properties at the solar source regions vary from one event to another and also vary depending on where they are measured in the heliosphere. Current research involves understanding how the CME/flare system erupts at the Sun (e.g., the breakout model of Antiochos et al., 1999); how the CMEs are accelerated near the Sun (Chen and Krall, 2003); and how SEPs are transported in the heliosphere (e.g., Li et al., 2003; Manchester et al., 2005). Model validation using data from real SEP events is needed to better understand (1) the sources for seed particle populations, (2) particle injection into and escape from the shock, and (3) the role of turbulence in the particle acceleration process.

Required observations for specifying the input parameters include vector magnetograms to specify the coronal magnetic field, and coronal imaging and spectroscopy (radio through gamma ray) for specifying the SEP/CME/solar wind source regions. Real-time in situ plasma and magnetic-field measurements are essential for model validation and for nowcasting simulations.

ONGOING INTEGRATED MODELING ACTIVITIES

It is an enormous challenge to predict the radiation environment from first principles starting with a disturbance at the Sun. This is so for three main reasons: (1) the multiple size scales involved for the relevant physical processes, (2) the different environments where these processes occur, and (3) an incomplete knowledge of the underlying physics. A complete end-to-end model should link the separate space weather models for the solar origin, heliospheric propagation, and interactions with planetary magnetospheres and atmospheres. Several research collaborations are involved in the development of such integrated models. They are listed below:

- *Community Coordinated Modeling Center (CCMC)*—A multiagency partnership that provides access to modern space science simulations for research and supports the transition to space weather operations of modern space research models (http://ccmc.gsfc.nasa.gov/).
- *Center for Integrated Space Weather Modeling (CISM)*—A multi-institutional center funded by the National Science Foundation (NSF) to create a physics-based numerical simulation model that describes the space environment from the Sun to Earth. Boston University is the lead institution (http://www.bu.edu/cism/).
- *Solar Multidisciplinary University Research Initiative (Solar MURI)*—A collaborative Department of Defense (DOD)-funded project studying magnetic eruptions on the Sun and their effects on Earth's space environment. The University of California, Berkeley, is the lead institution (http://solarmuri.ssl.berkeley.edu/).
- *Space Weather Multidisciplinary University Research Initiative (Space Weather MURI)*—A collaborative DOD-funded project with a long-term goal to achieve significant progress in the quest for a predictive space weather modeling capability that can eventually be transitioned to use by civilian and DOD space weather forecasting centers. The University of Michigan is the lead institution (http://csem.engin.umich.edu/muri/).
- *Solar, Heliospheric, and Interplanetary Environment (SHINE)*—An NSF-funded project to support an affiliation of researchers within the solar, interplanetary, and heliospheric communities whose goal is to enrich and strengthen both physical understanding and predictive capabilities for connecting events on the Sun with solar wind and disturbances in the inner heliosphere (http://www.shinegroup.org/).

Two other programs that provide funding opportunities for the development and testing of integrated models are the NASA-funded Interdisciplinary Exploration Science program and the Living With a Star Targeted Research and Technology program (with joint funding by NASA and NSF).

WHAT IS POSSIBLE FOR THE FUTURE?

Current efforts are leading to better, more realistic models of CMEs, flares, and SEPs. Future models will use more realistic physics and will be enabled by computers with increasing computational speed and capabilities that allow for the rendering of space weather events in three spatial dimensions, with high spatial and temporal resolution. These models will be global in the sense that they will be capable of forecasting events anywhere in the inner heliosphere that are regions of interest to the Vision for Space Exploration (VSE).

Some global models are beginning to come online now, but they are difficult to tailor to specific events. One clear statement from the workshop is that there is a need for a better understanding of how to relate the observations to the models. The observations have a dual role: (1) they provide the inputs to drive models, and (2) they are required to validate the models (post facto). Some of the anticipated near-term and long-term results from the space physics community are described below.

Near-Term Results (Up to 2015)

For the near-term need (up to 2015), it should be possible to improve predictions of "all clear" periods when there is a very low probability that an SEP event will occur. This is possible with a better understanding of the signatures indicating that a flare or CME is about to erupt. New observations of solar magnetic structures with Solar-B, the Solar Dynamics Observatory, and the ground-based Advanced Technology Solar Telescope and the Frequency Agile Solar Radio Telescope will help in this regard.

Missions such as the Solar Terrestrial Relations Observatory (STEREO) will provide simultaneous data from two different positions off of the Sun-Earth line as interplanetary CMEs propagate outward from the Sun. These data will be useful for developing models that can specify, and in some cases forecast, the SEP environment at a wide range of longitudes in the inner heliosphere. This is an important point since Mars, a future exploration target, is rarely on the Sun-Earth line.

The physics-based models discussed above must be pared down to include only the most essential parameters that are capable of predicting the variability of the space radiation environment. These models must be validated before being transitioned to operational use.

Far-Term Results (After 2015)

Farther out in the future (after 2015), it is desirable to make predictions of solar events weeks before they occur. More than likely this will be possible only with models that use a statistical approach along with a suitable set of in situ and remote sensing measurements from multiple vantage points in the heliosphere. It will be most useful for the VSE if models can predict the following: (1) the onset time for an SEP event, (2) its time-intensity profile, (3) the "spectral indices" of the energy spectrum, (4) the shock arrival time, and (5) the anisotropy in the particle velocity distribution (lower priority).

An effective SEP warning system will require an operational distributed network of observations from the Sun throughout the heliosphere (similar to the distributed network of weather stations on Earth). Near-Sun missions such as Inner Heliosphere Sentinels, Solar Orbiter, and Solar Probe will provide unique measurements to test more sophisticated models. One novel approach for a future mission, presented at the workshop, is to put multiple (~15) spacecraft around the Sun at 1 AU. Spacecraft situated in polar solar orbits, at the Earth-Sun L2 and L3 points, or spacecraft at the Mars-Sun L1 points can provide unique data for a global heliospheric warning system. Remote sensing observations of CME/flare/SEP source regions in the extended corona (2 to 10 solar radii) can provide unique precursor signatures for the severity of radiation events.

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Operational Strategies for Space Weather Support

Future exploration missions require adequate science-based understanding, appropriate observations, and physics-based models to make it possible to develop operationally robust tools that provide timely forecasts of the space environment. These must contribute to an overall risk mitigation architecture designed to ensure the safety of astronauts throughout all phases of exploration missions. The following elements need to be included:

- Adequate shelter,
- Effective radiation monitoring,
- Reliable communications, and
- Integrated mission planning and operations concepts.

This chapter provides an overview of how radiation monitoring and warning are carried out today to support the space shuttle and the International Space Station (ISS), discusses the general components of a space weather architecture, describes architectures specific to lunar and Mars missions, and discusses the need to transition research to operational support more effectively.

CURRENT OPERATIONS SUPPORT (SPACE SHUTTLE AND INTERNATIONAL SPACE STATION MISSIONS IN LOW EARTH ORBIT)

The Space Radiation Analysis Group (SRAG) at the NASA Johnson Space Center is responsible for ensuring that the radiation exposure received by astronauts remains below established safety limits. This responsibility includes making preflight and extravehicular activity (EVA) crew exposure projections and carrying out real-time radiation environment monitoring during missions.

Factors affecting crew radiation exposures in low Earth orbit (LEO) include the following:

- The structure and materials of the spacecraft,
- Mission altitude(s) and inclination,

- EVA start time and duration,
- The status of outer zone electron belts,
- Interplanetary particle flux,
- Geomagnetic field conditions, and
- The phase of the solar cycle.

The last four factors are the province of solar and space physics scientists (NRC, 2000).

Preflight and Extravehicular Activity Crew Exposure Projections

SRAG maintains an extensive set of tools for estimating the exposure received by the crews of manned missions in LEO. This suite of tools includes time-resolved models of Earth's magnetic field, maps of the radiation fluxes trapped in the geomagnetosphere, and trajectory translator/propagator algorithms. Space environment conditions (interplanetary proton flux, status of the electron belts, geomagnetic field conditions) from the Space Environment Center (SEC) of the National Oceanic and Atmospheric Administration (NOAA) are integrated with mission parameters (altitude and inclination of the spacecraft, location and timing of EVA) in order to project crew exposures.

Astronauts in LEO are exposed to radiation trapped in Earth's magnetosphere and to radiation from the Sun (solar energetic particles [SEPs]) and beyond (galactic cosmic radiation [GCR]). The trapped radiation is most intense in a region off the coast of South America (the South Atlantic Anomaly [SAA]), owing to a slight offset between the magnetic dipole of Earth and Earth's axis of rotation. The SEPs and GCR are most intense near Earth's poles, where there are "holes" in the approximately dipolar magnetosphere. The extent of exposure in the polar regions fluctuates during periods of geomagnetic storms. Figures 3.1 and 3.2 demonstrate the radiation environments that the International Space Station is exposed to during its orbit of Earth.

Low-inclination, high-altitude flights during solar minimum produce higher dose rates than those with high-inclination, low-altitude flights during solar maximum. At higher altitudes, the area of the SAA is larger and the flux of protons is higher. Although trajectories of high-inclination flights pass through the regions of maximum intensities within the SAA, less time is spent there than during low-inclination flights, and crews on high-inclination flights typically receive less net exposure to trapped radiation for the same altitude.

During solar maximum, increases in the Sun's activity expand the atmosphere; this expansion causes losses of some of the protons in the radiation belts owing to interactions with atmospheric gases. Therefore, trapped radiation doses decrease during solar maximum and increase during solar minimum. The impact of GCR is also lower during solar maximum, because the increased speed and density of the solar wind intensifies the interplanetary magnetic field generated by the Sun, making it more difficult for GCR to penetrate the inner solar system.

Radiological Support During Missions

The radiation consoles in the Mission Control Center at Johnson Space Center (JSC) are staffed 4 hours daily during nominal space weather conditions and continuously during EVAs and significant space weather activity. SRAG receives data and alerts NOAA's Space Environment Center in Boulder, Colorado. NOAA continuously monitors data received from its space weather satellites and ground stations to provide current information and forecasts about the space environment. SEC forecasters provide around-the-clock support, providing alerts and warnings about space weather conditions by telephone and pager and by displaying real-time operational space weather data via the Internet.

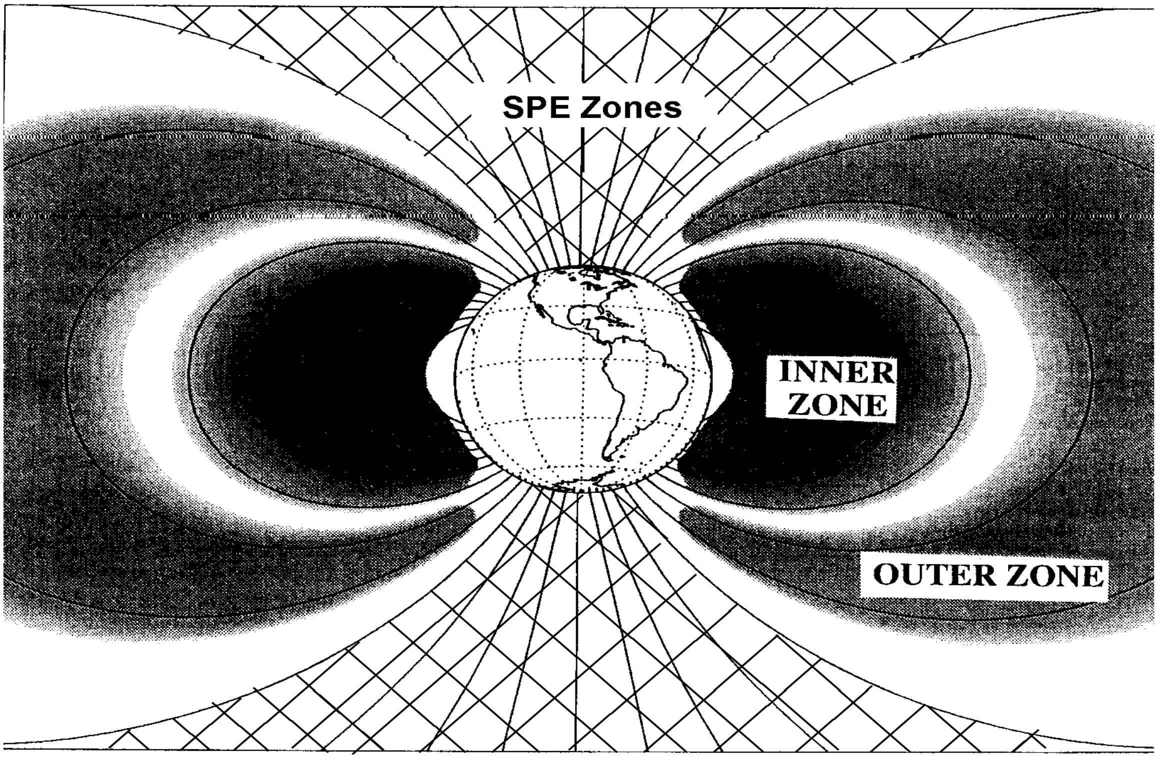

FIGURE 3.1 The radiation environments of the International Space Station: the three regions of space around Earth where penetrating radiation occurs. SOURCE: NRC, 2000, Figure 1.1, p. 8.

Crew Exposure Modeling Capability

SRAG's modeling tools include radiation transport codes and computer-aided-design-based geometry evaluation tools. These tools are used as part of an information feedback loop, and real measurements are used to refine the process continuously. This allows SRAG to react to changes in the on-orbit environment and to anticipate and plan for periods of potentially hazardous exposure.

Radiation Monitoring Instruments and Dosimeters

The present suite of detectors used to monitor the radiation environment during manned missions includes passive dosimeters (crew passive dosimeter [CPD] and radiation area monitor [RAM])[1] and active

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[1] A CPD is a small set of thermoluminescent detectors (TLDs) encased in a Lexan holder. The material responds to radiation via electronic excitation states in the various TLD materials. After exposure, the amount of absorbed energy (dose) is determined by applying heat and measuring the amount of visible light released as these excited states are returned to equilibrium. A CPD is carried by each member of the crew during the entire mission and analyzed upon return to Earth. Identical to the CPD, RAMs are placed throughout the volumes of both the ISS and the space shuttle; the ISS RAMs are swapped out during the periodic shuttle servicing and supply missions.

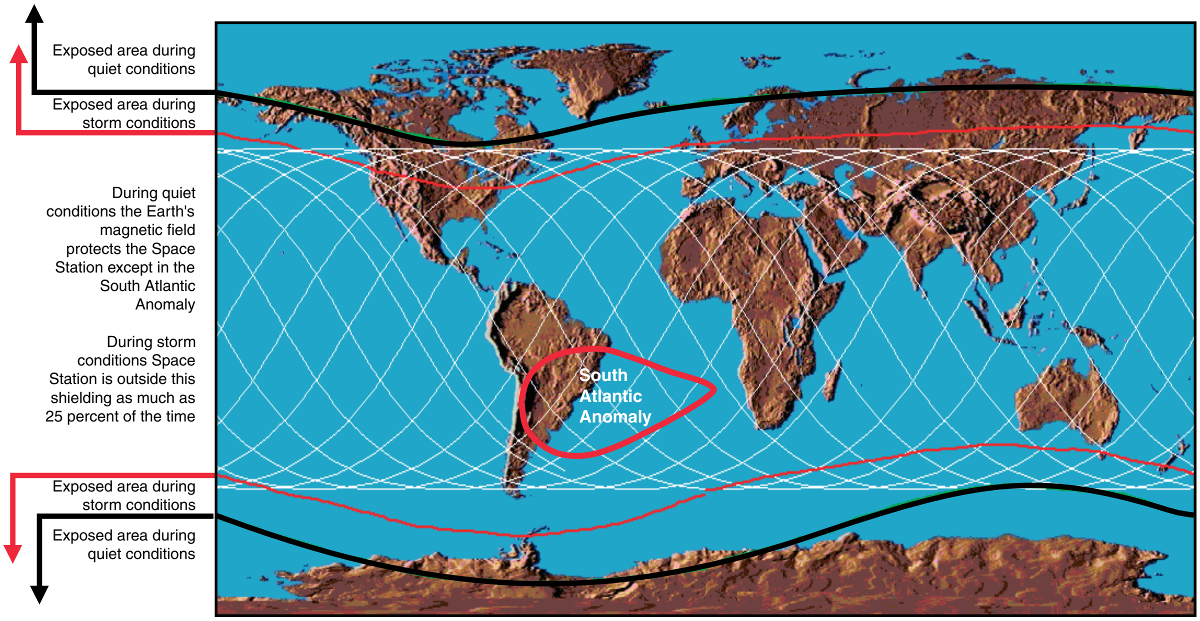

FIGURE 3.2 International Space Station (ISS) exposure to radiation. Twenty-four hours of ISS ground track overlaid with the magnetic shielding boundaries for quiet and active storm conditions and the South Atlantic Anomaly. The quasi-latitudinal pair of high-latitude lines in each hemisphere indicates the low-latitude borders of areas accessible to radiation from solar energetic particle (SEP) event zones. The higher-latitude line in each hemisphere represents quiet conditions and the lower-latitude line represents disturbed conditions. SOURCE: NRC, 2000, Figure 1.5, p. 14, originally provided by Ronald E. Turner, ANSER Corporation.

instruments to measure dose (tissue equivalent proportional counter [TEPC]),[2] and record the charge, energy, and directionality of particles (charged particle directional spectrometer [CPDS]).[3] Passive dosimeters are mounted throughout the ISS and space shuttle (RAM) and are also worn by crew members throughout the mission (CPD). The TEPC and CPDS display the average dose rate and other parameters in real time for use by the crew, and transmit data to Mission Control so that SRAG personnel can constantly monitor the radiation environment inside the spacecraft. The TEPC is portable, enabling the mapping of the internal spacecraft radiation environment. The TEPC and RAM are flown on both the ISS and the space shuttle; the CPDS is flown only on the ISS.

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[2] The TEPC measures the dose that a small volume of human tissue would absorb if the tissue were at the detector's location. The instrument incorporates a spectrometer that performs real-time calculations and a liquid crystal display.

[3] The CPDS is a stack of energy-loss and position-sensitive silicon detectors and a Cerenkov counter, designed to measure the charge, energy, and direction of a particle that passes through the instrument. Currently, there are four CPDS instruments in use onboard the ISS. The intra-vehicular charged particle directional spectrometer (IV-CPDS) is designed to be used inside the ISS, with liquid crystal displays and mounting and power options for both the U.S. and Russian segments. The remaining three CPDS instruments are mounted outside the ISS and form the extra-vehicular charged particle directional spectrometer (EV-CPDS). The EV-CPDS instruments are arranged in such a way that one points forward along the velocity vector (EV1), one points aft along the antivelocity vector (EV3), and the third points up along the zenith direction (EV2). The EV-CPDS instruments have no liquid crystal displays and are coated with a special material to allow the instruments to survive the extreme temperatures in space.

SRAG staff at JSC prepare the passive dosimeters prior to flight and analyze them when they return. The staff submits reports containing the results of the analyses to the space radiation health officer and to the crew flight surgeon. These reports are retained as a permanent record of the crew members' health history and may be used to determine eligibility for additional flights.

Solar and Space Physics Support Areas for the Future

According to a workshop presentation by the SRAG, operational support in the shuttle and ISS era by the solar and space physics (SSP) scientists could be enhanced by the following:

- Real-time data from SSP spacecraft,
- Additional real-time measurements in proton flux (50 to 100 MeV but also 300 to 500 MeV),
- Integration and transition from research models to configuration-controlled operational tools,
- SSP spacecraft data being sent directly to vehicles as well as to the ground,
- Quiet-time forecasts, and
- Active and electronic personal dosimeters with well-characterized charged particle and neutron sensitivities.

The workshop's breakout group on dosimetry, which included SRAG management and staff, drew up the following list of knowledge requirements for additional support to exploration (lunar and Mars) missions:

- Dosimetry
  - Using modern techniques, reanalyze data from dosimeters (emulsions and plastic nuclear track detectors) carried on Apollo lunar missions.
    - Fill in high *Z* energetic gaps for particles with Linear Energy Transfer below 200 keV/μm.
    - Provide reevaluated dose equivalents for Apollo astronauts.
  - Analyze data from the Mars Radiation Environment Satellite instrument on Mars Odyssey to provide estimates of dose equivalent in Mars orbit.
- SEP event predictive tools for operational decisions
  - Prediction of the next most likely SEP event temporal evolution profile (at selected energies), with associated probabilities.
  - Real-time data from the actual event (at the selected energies).
  - Refining of predictions in real time as the real-time data arrive.
  - Quiet-time (all clear) forecast.
  - Prediction of the differential flux (particles/time/area) at several critical particle energies in real time and 3, 6, 12, and 24 hours before the event at 1 AU in free space for lunar missions and between 0.75 and 1.5 AU for Mars missions.
- Energies of interest for operational forecast
  - Protons (30, 60, 100, 500, 1000 MeV).
  - Helium (30, 60, 100, 500 MeV per nucleon).
  - Electrons (0.5 to 5.0 MeV).
- Lead time—real time, and at –3, –6, –12 and –24 hours.
- Time period and interval—every 5 min. from onset to return to background.
- GCR and SEP event environment—Determine the limits of the long-term variability in the space radiation environment, including GCR and SEP events, through continued research into the long-term

secular changes in the GCR spectrum, using ^{10}Be, Voyager, and historical data, supporting a goal to predict nominal and worst-case exposure.

- Robotic missions that allow U.S. access to the necessary data to enable the above. Monitoring at L1 is preferred because it is outside the magnetosphere, is at approximately 1 AU, and gives continuous coverage.

SYSTEMS APPROACH TO PROVIDING SPACE WEATHER SUPPORT TO THE VISION FOR SPACE EXPLORATION

Meeting all or many of the capabilities identified above will require a future system, or architecture, that incorporates various components:

- *Solar monitoring* (monitoring what is going on at the Sun to observe activity that may lead to an SEP event).
- *Heliospheric monitoring* (monitoring the state of the solar wind, interplanetary magnetic field, and fluctuations in the nominal solar wind, to be able to predict the propagation of accelerated protons from the source to the astronauts).
- *Energetic particle monitoring* (monitoring the solar proton and ion flux in the region near the astronauts).
- *Communications and data fusion* (addressing issues that may affect the ability to get the needed data to the appropriate user in a useful format).

There are established instruments that can be applied to the task of minimizing the risks that SEP events pose to astronauts. In a few cases, notably observations of the state of the heliosphere, there are some new instruments being investigated that may significantly enhance the current ability to monitor and forecast the evolution of an SEP event. In almost all domains there is a need to develop more effective operational approaches to collect and apply the appropriate data.

Components of a Space Weather Risk Mitigation Architecture

Any risk mitigation architecture has several components. All of these components have to be utilized to reduce overall risk, and some of them offer greater risk reduction potential than others.

Solar monitoring is required in order to place the forecasts and observations of SEP events into a context of ongoing and potential solar activity. Near-real-time observations of solar active regions and emerging coronal mass ejections (CMEs) may provide data useful to project the progress of an SEP event over a period of hours to days. Additional progress in understanding the physics of CMEs may lead to a multiday forecast of the probability of an SEP event, or enhanced, highly reliable forecasts of “all clear” periods. A variety of instruments are needed to support these tasks, from solar surface imagers (observing the Sun in visible, ultraviolet, x-ray, and radio wavelengths) to near-Sun solar coronagraphs. There is an extensive suite of research spacecraft and ground-based facilities providing experience and proof of concept from which it will be possible to select the appropriate operational instruments for an SEP event risk mitigation architecture.

Heliospheric observations provide information necessary to model or monitor the propagation of SEPs from the source to the astronauts. Density fluctuations from solar emissions and from boundaries between slow and fast solar wind streams affect the shape of the interplanetary magnetic field along which the energetic particles move. They also affect the strength, structure, and motion of CMEs and the associated shocks that accelerate the energetic particles. The data that may be necessary for SEP event propagation models include information on the general state of the ambient plasma providing the source particles that are accelerated, the interplanetary magnetic field, and local disturbances moving through the inner heliosphere. Both in situ and remote sensing methods may contribute to the characterization of the heliosphere. The in situ instruments are typically small, low-cost sensors with long heritage. Remote sensing techniques that may provide a measure of CME shock characteristics, including speed, size, and strength, include observations of scattered visible zodiacal light and radio observations of interplanetary scintillations.

Direct measurements of in situ solar energetic particles will continue to provide the most important contributions to an SEP event risk management strategy. Measurements at the astronauts' location will be able to confirm that a solar particle event is under way and to provide information about the flux, rate of change of flux, and total fluence of the event. In addition, instruments may be needed to measure the relative contribution to the total flux from particles with different energies, from 10 MeV through several hundred MeV. Finally, it may be necessary to identify the flux of high-energy, high-mass ions that make up an ongoing SEP event. Additional energetic particle measurements at locations significantly away from the astronauts may also contribute to forecasting the evolution of an ongoing event. Various instruments are available to provide these measurements, including particle telescopes, solid-state detectors, and proportional counters.

The natural radiation measured outside a spacecraft generates a shower of secondary particles as the radiation is slowed (and possibly stopped) by shielding surrounding an astronaut. The total radiation exposure to the astronaut is a combination of this secondary radiation and the surviving natural radiation. The complexity of shielding, uncertainties in the flux, and the need to know the crew exposure as well as possible will require ***real-time dose and dose-rate measurements*** to substantiate or replace the modeled dose estimates and projections based on measures and forecasts of the external environment. Options include the traditional film-badges, tissue-equivalent proportional counters, solid-state detectors, and possible biodosimetry techniques.

The ***communications infrastructure*** is an important factor to consider in the construction of a total SEP event warning system. Since the highest-energy particles move with speeds close to the speed of light, techniques are needed to ensure that warnings and support are provided in a timely fashion. Science-based missions can employ cost-saving measures that store data for periods of time and transmit them as opportunities arise. Data from multiple spacecraft observing the same event are stored at various locations and are occasionally pieced together in "campaigns" months after the observations. However, operations data must be routinely delivered promptly from all of the spacecraft that make the observations to the operational center or centers that use that information. Some of these spacecraft may be at locations far from Earth. Once the data are received and processed, to provide real-time alerts and warnings there must be ensured communications access to the astronauts at a lunar base, on a lunar surface expedition, or at or on the way to Mars. On a Mars mission, the communication to the astronauts will take up to 20 minutes to arrive from Earth.

Because of the threat posed by SEP events, consideration of radiation safety will be critical to ***ensure adequate shielding or timely access to a safe haven.*** Fortunately, awareness of the risk of radiation exposure is widespread, and it is likely that systems will be designed with attention to radiation risk management. It is critical to decide at the outset what the radiation risk mitigation strategy will be and then to integrate this strategy into the mission concept early in the design phase. The generic elements of a radiation risk mitigation strategy include space environment situational awareness, radiation exposure forecasting, and exposure impact and risk analysis. These elements combine to generate recommendations to the mission commander to keep the radiation exposure as low as reasonably achievable. The generic components of the radiation safety information flow leading to specific recommendations to the person ultimately in charge of the actions to be undertaken, whether delegated to an astronaut on the mission, or reserved for a person in mission control, are shown in Figure 3.3.

The return to the Moon will be characterized by longer missions and significant surface excursions compared with the Apollo missions. Risk management architectures are likely to take advantage of a space weather network designed to protect Earth, with additional elements added to measure or estimate astronaut exposure and to provide communication links to the Moon base and astronauts on surface EVA.

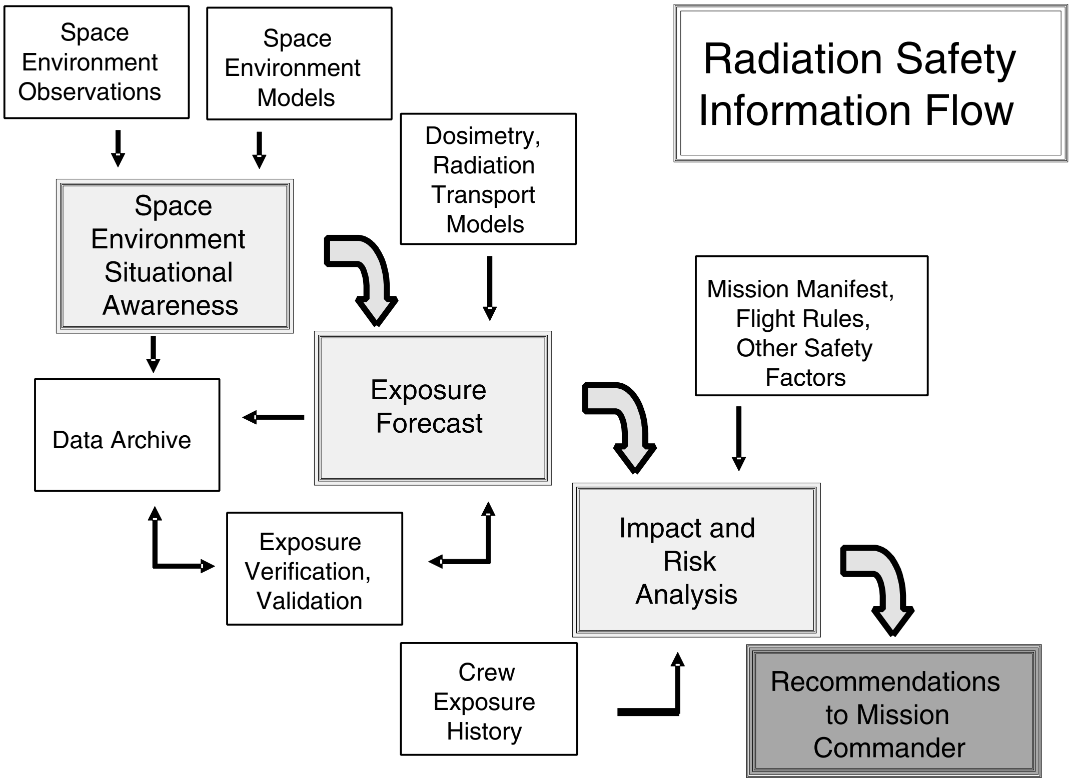

FIGURE 3.3 Components of the radiation safety information flow leading to specific recommendations to the mission commander. Each element has contributing components: observations, models, rules that must be followed, goals that must be achieved, and so on. For example, space environment situational awareness will be data- and model-driven. The data may come from a variety of sources, including operational and research spacecraft as well as ground-based observatories and instrumentation co-located with the astronauts. These data must be integrated into a useful forecast of the radiation threat level. Radiation exposure forecasts will rely on in situ dosimetry, transport models that start with the forecast particle environment, and models that convert the radiation field into a measure such as dose equivalent. Mission impact and risk analysis will be based on the exposure forecast, considering flight rules, mission manifest, and crew exposure histories. This process leads to recommendations to minimize the radiation risk. These recommendations will be considered in the context of mission objectives and competing risks, and ultimately a course of action will be selected. SOURCE: Courtesy of Ronald E. Turner, ANSER Corporation.

Human expeditions to Mars will be the most ambitious space missions of our time. To execute these missions successfully, the radiation environment must be considered and risks appropriately managed from a systems perspective. Since the spacecraft will be the only source of shelter on a Mars mission for the hundreds of days during which the crew will be in deep space, it is critical that it contain adequate shielding to reduce the radiation dose from exposure to the steady GCR flux and the multiple large SEP events to acceptable levels. Such levels, however, and the shielding required to attain them, have yet to be determined. Particle flux and crew exposure must be measured in near real time throughout the mission. Additional elements must be evaluated for cost benefit and value to the crew. As with the return to the Moon, it is reasonable to assume that the Earth-based solar-monitoring network will support a Mars mission with SEP event forecasts and alerts. However, there are two substantial differences: Earth will not always be in a position to directly monitor critical regions of the Sun, and separation distances of several AU may significantly limit the timeliness of communication between Earth and the astronauts. One method to overcome the limitation of Earth-viewing geometry is to include solar- and heliospheric-monitoring instrumentation on the Mars-bound spacecraft. Instrumentation on additional platforms may be needed to monitor further "blind spots." For example, solar imagers at widely spaced heliolongitudes can provide situational awareness of the solar active regions at or around the solar limb as viewed by the Mars-bound spacecraft. Additional in situ data points could provide valuable information on the state of the interplanetary magnetic field, solar wind conditions, and propagation conditions for shocks and SEP events. Ensuring that widely dispersed data-collection platforms meet significant timeliness requirements will place severe constraints on a communications architecture.

The elements that are ultimately chosen will depend on the strategy employed. Figure 3.3 demonstrates how safety information about radiation flows through a properly constructed system to result in recommendations to the mission commander. Figure 3.4 provides an overview of the "tool kit" that could be constructed to support either a lunar or Mars mission. Figure 3.5 provides one version of a structure that ties these resources together in a system architecture.

The final determination of the appropriate elements of the risk mitigation architecture will depend on many things. On the forecast side, the most significant consideration will be the state of the art in predicting the eruption and character of coronal mass ejections and the evolution of associated SEP events. In the past, the NOAA Space Environment Center has been called on to provide data on space weather conditions for missions beyond Earth orbit; in the future it could be called on to extend its space weather forecast and specification services to support the Vision for Space Exploration (VSE). Important considerations on the exposure-reduction side will include the latest understanding of shielding options, pharmacological countermeasures, and an ability to prescreen astronauts for radiation tolerance.

Lunar Hardware Elements

The phases of a lunar mission from a space weather perspective are described in Box 3.1. Potential hardware elements of an architecture to provide protection from unfavorable space weather during a lunar mission would be drawn from the general elements shown in Figures 3.4 and 3.5. The appropriate cost-effective solution will depend on the lunar mission scenario and on the limits of current understanding of the physics of SEP events. At a minimum, the main lunar base will contain adequate shielding for protection from long-term exposure to GCR and will provide a safe haven from SEP events. Astronauts and surface transportation elements will likely be equipped with real-time and passive tissue-equivalent dosimeters to permit monitoring of dose rate and cumulative dose. Unfortunately, such a system could miss a potentially severe situation if the SEP flux dramatically increased when the CME shock passed the astronaut's location (an occasional occurrence, known as a "shock-enhanced peak," due to energetic particles trapped in the

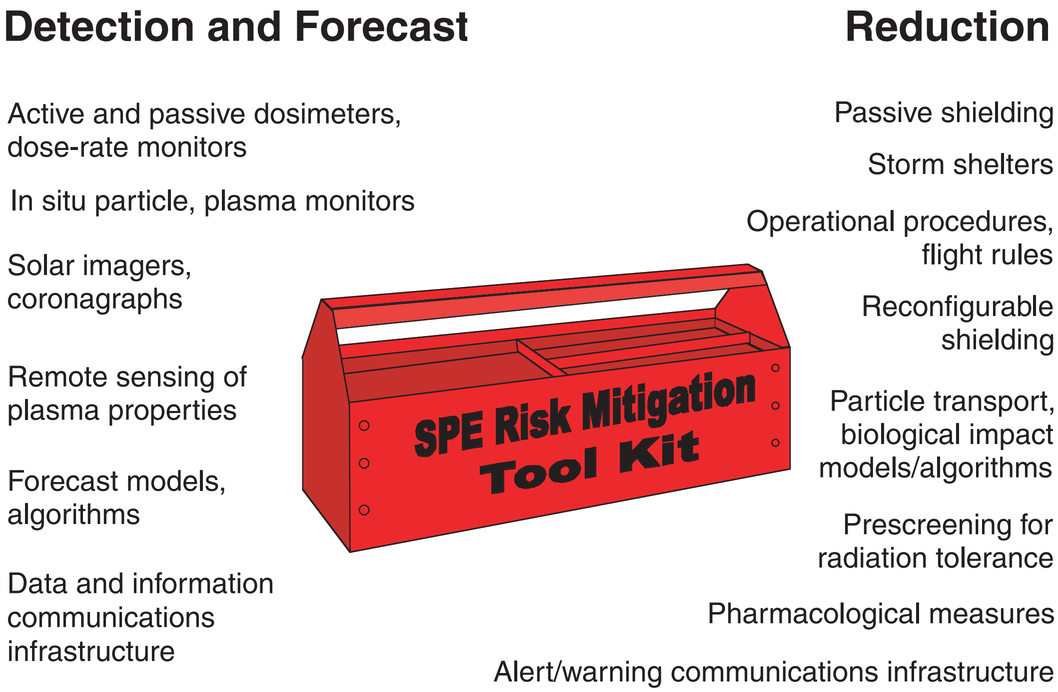

FIGURE 3.4 An overview of a comprehensive "tool kit" from which a solar particle event risk mitigation infrastructure could be constructed to support either a lunar or a Mars mission. The elements are divided between components that could contribute to the detection and forecast of the radiation environment and those that contribute to the reduced impact of an astronaut's exposure to the radiation environment. The final determination of the appropriate elements of the risk mitigation architecture will depend on many things, including overall mission architecture and the radiation mitigation strategy. SOURCE: Courtesy of Ronald E. Turner, ANSER Corporation.

CME shock, such as occurred in October 1989; see Figure 3.6). This experience demonstrates why it is important to understand the interplanetary medium in order to make radiation dose predictions.

It is reasonable to assume that an Earth-based solar-monitoring network (including orbital elements such as geosynchronous particle detectors, the planned NOAA soft x-ray imager, and research-quality solar monitors as employed on the Solar and Heliospheric Observatory and planned for future NASA solar missions) will be available to support SEP event monitoring, alerts, and forecasts. A plasma monitor at or beyond the Sun-Earth L1 point, and space-based extreme ultraviolet (EUV) and/or x-ray imagers along with a wide-field coronagraph would be the most important enhancements to the currently projected Earth-based solar observing network. An L1 sentry, stationed 1.5 million km toward the Sun, would provide data on the state of the interplanetary plasmas and fields to be used to detect shock waves, particle flux enhancements, and arrival time of CMEs. The EUV and/or x-ray imager would monitor developing active regions. A wide-field coronagraph could detect emerging CMEs. The combined data could support long-term forecasts by providing information on the state of the Sun and particle propagation conditions.

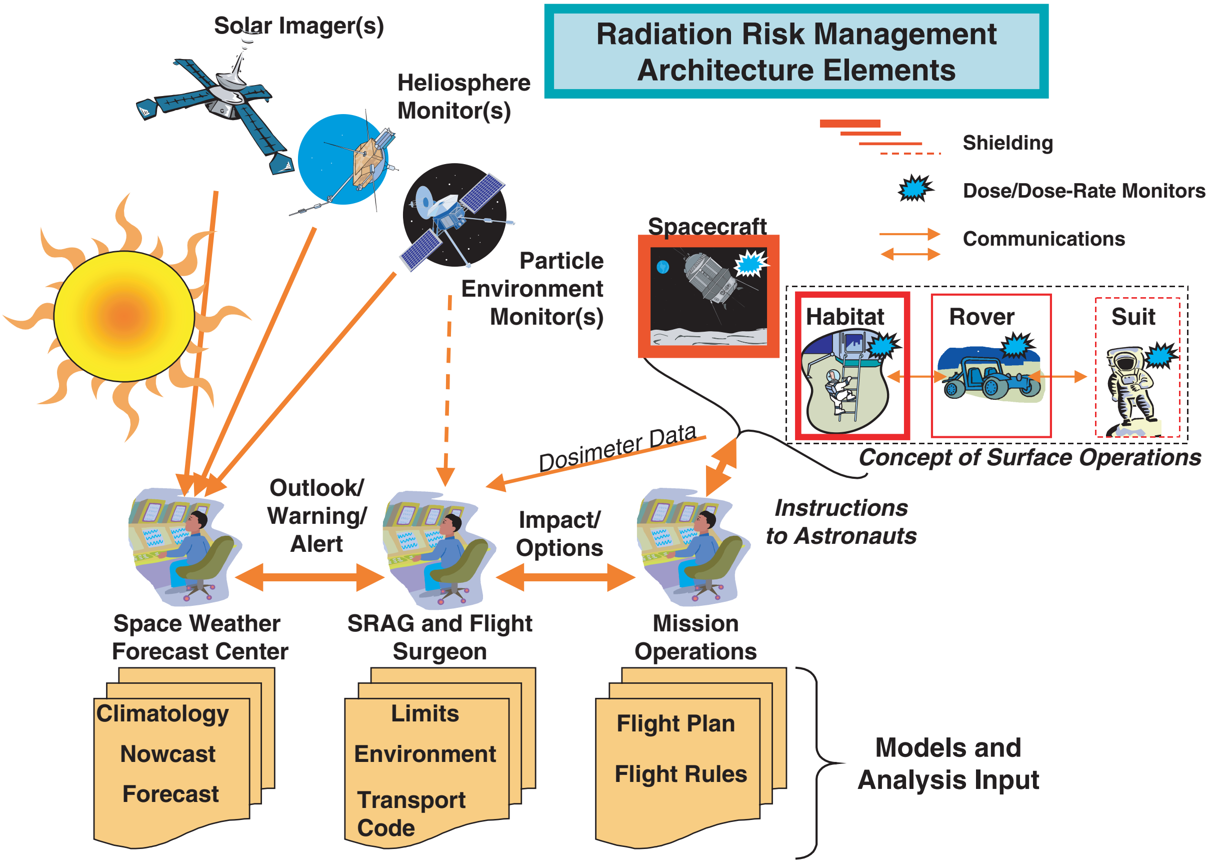

FIGURE 3.5 One potential construct of a space radiation warning architecture. SOURCE: Courtesy of Ronald E. Turner, ANSER Corporation.

To provide real-time support, any Earth-based elements must have ensured communications access to the lunar base and all surface teams. This communications architecture could be built around the architecture that is used to support routine operational communications between Earth and the Moon.

Astronauts engaged in surface exploration or activities outside established habitats will be at additional risk from solar energetic particle events. The many reasons for extended trips away from a main lunar base include mapping, scientific exploration, mining, and construction of facilities. The frequency of expeditions, distance traveled, duration of the stays, and exposure onsite will vary with the purpose of the trip. Each of these factors will affect the resources accessible to the team and the responses available in the event of an SEP event.

BOX 3.1
LUNAR MISSION PHASES

Astronauts will be exposed to radiation hazards during all phases of a lunar mission:

- *Low-Earth-orbit assembly and checkout*. Solar and galactic radiation protection will be provided by Earth's magnetic field, but the astronauts will be exposed to the low-Earth-orbit component of the trapped radiation belt, as experienced by the International Space Station.
- *Lunar transfer orbit*. Astronauts will experience a brief period of high radiation exposure during trapped radiation belt transit. They will be exposed to free space on the trips to and from the Moon (up to 3 days each way).
- *Lunar orbit*. Astronauts will be exposed to a modified version of the free-space radiation environment. At sufficiently low altitude there will be significant shadowing by the Moon, but there will also be some additional exposure from radiation emitted from the lunar surface, created by the interaction of the galactic cosmic radiation (GCR) and lunar surface material.
- *Lunar base habitation*. The radiation environment of the lunar surface will be approximately half that of the free-space environment, with additional exposure from the surface radiation created by the GCR impact on the lunar material, particularly from neutrons.
- *Lunar surface exploration*. The likelihood of reduced shielding of surface transportation (relative to that of the main base) may expose the crew to solar energetic particle events. Risk mitigation options include aborting to base, embedding a storm shelter in the transport vehicle, carrying the means to construct temporary shelter, and pre-establishing safe shelter outposts.

Mars Hardware Elements

The phases of a Mars mission from a space weather perspective are described in Box 3.2. The potential elements of an architecture to provide solar radiation protection throughout a human mission to Mars would be drawn from the general elements shown in Figures 3.4 and 3.5. As with the return to the Moon, detailed trade studies will be needed to determine the optimal mix of components from this list. The appropriate solution will depend on the Mars mission scenario and the limits of current understanding of the physics of SEP events.

Since the spacecraft will be the only source of shelter on a Mars mission for the hundreds of days that the crew will be in deep space, it is critical that it provide adequate shielding to protect the crew from the steady GCR exposure and the sudden impact of multiple large SEP events. NASA has known for some time that shielding on the order of 100 to 200 g/cm^2 or more would be necessary to reduce dose equivalent in space to Earth background levels (Nealy et al., 1989; Simonsen et al., 1990). Beyond about 20 g/cm^2, however, there are diminishing returns, and shielding thicknesses increase very quickly for very little reduction in dose equivalent until one is actually at very large shield thicknesses. Much of the bulk needed for this shielding (particularly the shielding for a storm shelter) can be provided by clever configuration of necessary structural components, tanks, fuel, water, equipment bays, and so forth.

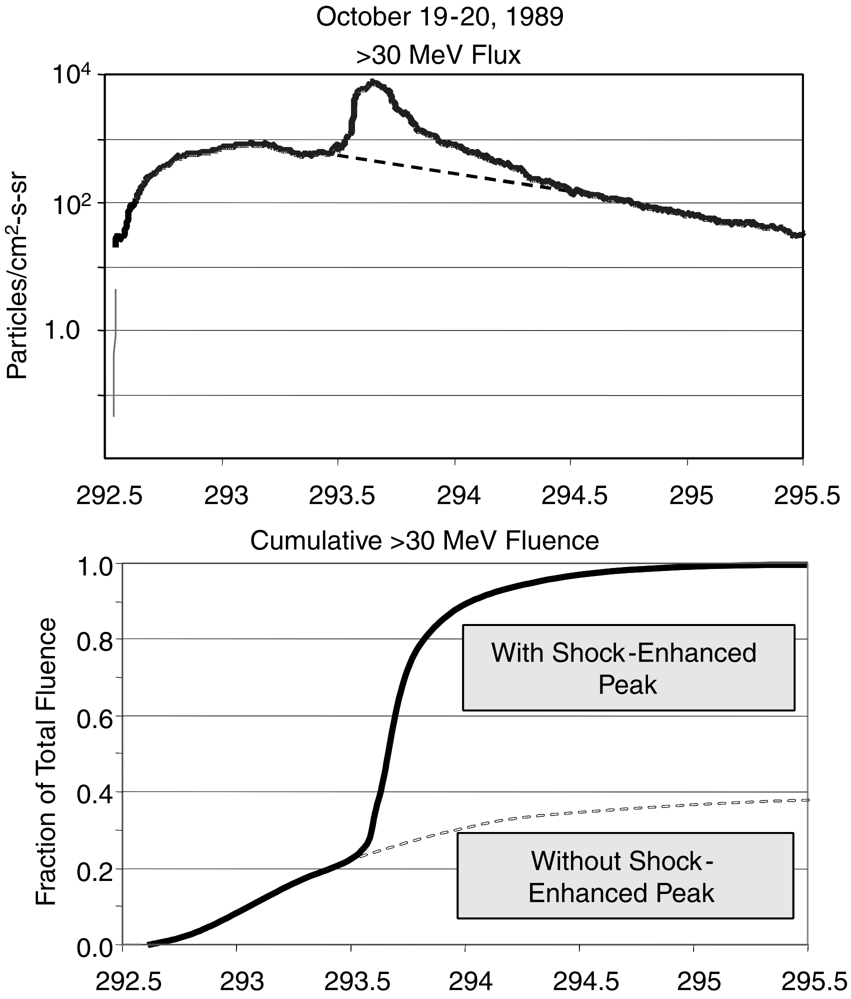

FIGURE 3.6 Flux and cumulative fluence of the October 19-20, 1989, solar energetic particle event, as measured by Geostationary Operational Environmental Satellite spacecraft. SOURCE: Turner, 2001. Copyright 2001, American Geophysical Union. Reproduced by permission of American Geophysical Union.

To monitor astronaut exposure during the mission to Mars, real-time and passive tissue-equivalent dosimeters will likely be provided to each of the astronauts and distributed throughout the interior of the spacecraft crew compartments, the landing vehicle, surface base elements, and any surface transportation vehicles. This complement of dosimeters and particle detectors can be used as part of a real-time SEP event alert and warning capability. However, since this limited approach is similar to what is done today, significant advances in the understanding of SEP events will be necessary to improve on the currently available false-alarm rate, miss rate, and poor flux estimation capability.

BOX 3.2
MARS MISSION PHASES

Astronauts will be exposed to radiation hazards during all phases of a Mars mission:

- *Low-Earth-orbit assembly and checkout.* Partial radiation protection will be provided by Earth's magnetic field.
- *Earth to Mars and Mars to Earth transit.* Galactic cosmic radiation (GCR) and solar energetic particle (SEP) events pose substantial risk to the health of the crew during transit between Earth and Mars. Mission timing relative to the solar cycle may have a significant impact on mission planning. GCR flux is approximately twice as large near solar minimum as it is near solar maximum. However, there is a reduced risk of a large SEP event near solar minimum.
- *Deep space extravehicular activity (EVA).* An astronaut on EVA in deep space would be exposed to potentially dangerous doses of radiation if a large SEP event occurred. If an EVA is necessary, the environment should be closely monitored, and provisions should be made for a quick return to a sheltered area (for example, to the air lock providing ingress/egress to the spacecraft).
- *Mars orbit.* A low-altitude orbit (about 500 km) will not provide significant protection analogous to the shielding in low Earth orbit, as Mars does not have an appreciable magnetic field. However, the total particle flux in orbit will be reduced by up to 40 percent through shielding by the planet's mass. Since solar and galactic cosmic radiation are essentially isotropic, this reduction will be effective throughout the orbit, not just during a period when Mars may block the electromagnetic solar radiation. While Mars eclipses the Sun, it also blocks observations of precursors of SEP events, which may complicate the generation of alerts and warnings.
- *Mars surface exploration.* Despite Mars's lack of a significant magnetic field, the thin atmosphere (2 percent of the thickness of Earth's atmosphere), and the planet's mass, which reduces particle fluxes by one-half, will provide additional shielding to protect astronauts on the martian surface from GCR and SEP event radiation. Since the incident space radiation is isotropic, it arrives at a point on the surface from all directions above the horizon with equal probablility. Hence, only a small fraction of the incident particles pass through the thinnest portion of the atmosphere, which is directly overhead. Most particles will arrive at the surface point having traversed much longer path lengths, especially particles arriving from directions near the horizon. Thus, the attenuation in the atmosphere is greatly enhanced over that which would occur if all of the incident particles arrived only from the zenith. However, there are possible extreme events or very hard events that may substantially increase the neutron flux on the surface of Mars.

As with the return to the Moon, it is reasonable to assume that the Earth-based solar monitoring network will support a Mars mission with SEP event forecasts and alerts. However, there are two substantial differences: Earth will not always be in a position to directly monitor critical regions of the Sun, and separation distances of several AU may significantly limit the timeliness of communication between Earth and the astronauts.

One method to overcome the limitation of Earth-viewing geometry is to provide solar and heliospheric monitoring instrumentation on the Mars spacecraft. The NASA Solar Terrestrial Relations Observatory

(STEREO) mission will provide experience with a similar suite of instruments and provide confidence that they can be deployed within a reasonable mass, power, and volume limit. An astronaut could be trained or an expert system could be developed to interpret the information and produce forecasts and alerts.

As the astronauts get farther from the Sun, the probability increases that a CME from an active region beyond the solar limb (as seen by the astronauts) might be the source of an SEP event. Instrumentation on additional platforms may be needed to monitor these "blind spots." A frequently discussed concept proposes a constellation of two or three solar monitors distributed along Earth's orbit but positioned to provide effective coverage of the Sun.

Supplemental data could be obtained relatively inexpensively by placing energetic particle detectors and plasma monitors on interplanetary targets of opportunity during the years preceding the Mars mission. A distribution of in situ data points could provide valuable information on the state of the interplanetary magnetic field, solar wind conditions, and propagation conditions for shocks and SEP events.

Other, more focused options are available to collect particle and plasma data to support a human mission to Mars. One approach would place a limited suite of instruments near the Sun-Mars L1 point (about a million kilometers toward the Sun from Mars), to play a role analogous to the proposed warning satellites near the Sun-Earth L1 point (about 1.5 million kilometers toward the Sun from Earth).

Maintaining timely and effective communications between the various elements of a solar radiation protection network will be a serious challenge. The distances are vast, and the geometry is frequently not favorable. The Earth-based Deep Space Network or its successor will be responsible for maintaining near-continuous communication with the astronauts on the spacecraft.

KNOWLEDGE-TO-OPERATIONS TRANSITION

Knowledge transfer, or how to transition research understanding, models, and observational capabilities from the solar and space physics scientists to support the Vision for Space Exploration, repeatedly emerged as an issue of importance during the workshop. In some ways, this topic is at the core of the purpose of the workshop, which was to identify ways in which SSP can make significant contributions to how NASA will deal with radiation—and other space environment conditions—that affect humans and systems on missions to the Moon, Mars, and beyond.

Prior to the VSE, and especially recently, knowledge-transfer issues have received much attention in the SSP community (see, for example, Chapter 5 in *The Sun to the Earth—and Beyond: A Decadal Research Strategy in Solar and Space Physics* [NRC, 2002]). Specifically, new understanding of solar and space physics processes on the Sun, in the interplanetary medium, and in Earth's magnetosphere, thermosphere, and ionosphere, combined with new advanced computational capabilities, has led to the development of models of the space environment that can benefit those affected by space weather. NASA's Living With a Star program is one example of a research and observation program that is structured to result in new space environment and space weather knowledge that will benefit society.

There are several other SSP programs that are focused on developing understanding and models that can, with additional effort, transition from the research-and-development community to operations. The National Science Foundation (NSF) funds a multiyear Science and Technology Center that is developing coupled Sun-to-Earth space weather models. The Department of Defense has supported several Multidisciplinary University Research Initiatives in solar physics and ionospheric physics to develop models that are ripe for transition to operations. The NSF has led three highly leveraged community solar and space physics groups—SHINE, GEM, and CEDAR (Solar, Heliospheric, and Interplanetary Environment program; Geospace Environment Modeling; and Coupling, Energetics, and Dynamics of Atmospheric Regions)—that are all actively involved in bringing together scientists to develop the next generation of research understanding and models that can be used by scientists as well as made ready for transition to the operational community. An interagency-sponsored Community Coordinated Modeling Center has evolved as a facility for validating models that can be used by scientists as well as bringing them a step closer to transition readiness. Finally, NOAA, with cosponsors from other agencies, has held an annual and growing Space Weather Week that brings together research, operations, and users in a forum that promotes communication among these disparate groups and advances the objective of transitioning research to operations.

In spite of these valuable endeavors, there is a considerable gap between what scientists have developed and what actually makes it into operations. Discussions at the workshop considered ideas for narrowing the gap so that knowledge from the solar and space physics scientists could be transferred to support the VSE. It was recognized that communication at workshops such as these, among an interdisciplinary group of participants, can identify where scientists can contribute to the high-priority needs of the users—whether it be those versed in radiation climatology talking to mission planners and hardware engineers, or space environment modelers talking to mission operations personnel. It was also clear that the practical benefit of scientific knowledge and models often requires much work beyond what is needed to make useful scientific tools. Activities such as model validation, robust code development, display design, and training all need to be supported beyond the level of scientific readiness.

By communicating and working closely together with those involved with all phases of the human and robotic missions, solar and space physics scientists have much to contribute to the VSE.

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4

Summary and Workshop Conclusions

The participants in the workshop reached consensus on a number of key issues. The six separate working groups selected representatives to present their summary conclusions at the end of the workshop (their individual reports are summarized in Appendix A). This chapter summarizes the conclusions of the working groups.

A central theme that emerged during the workshop, both in the formal presentations in the plenary sessions and in the focused discussions of the thematically organized working groups, is the importance of the timely prediction of the radiation environment for mission design and mission operations. **There was general agreement among the participants that it is in this area that the solar and space physics community can, through improved characterization and understanding of the sources of space radiation, contribute substantively to NASA's radiation management effort and to the Vision for Space Exploration.**

Further, many of the workshop participants agreed on the following:

- Developing timely predictions of the radiation environment is a complex task whose components vary depending on the timescale considered and on the mission characteristics;
- Delivering timely predictions requires advances in basic solar and space physics, development of observational assets, improved modeling capabilities, and careful design of communications;
- The space operations community—that is, those who plan and manage human spaceflight missions—must be informed about these advances in understanding and expanding capabilities so that operators can take advantage of advances; and
- In some cases operational tools (i.e., tools for space operations) must be developed or adapted from scientific analytical tools and converted to real-time reporting tools; the transition from research to operations is a very challenging task.

The workshop helped assess the current level of understanding of solar and space physics, contributed to an understanding of the issues faced by the NASA space radiation program as it deals with radiation effects on humans, led to fuller understanding of the challenges of ensuring the reliable functioning of instruments and machines in space, and, ultimately, illustrated how progress in understanding, defining, and making timely predictions of the space radiation environment is essential for implementation of the Vision for Space Exploration (VSE). Until now, there has been little need for the separate solar and space physics and human spaceflight communities to communicate and cooperate with each other. Many of the participants at the conference for the first time focused on ways that their research corresponded with NASA's needs to support humans traveling beyond low Earth orbit for the first time in decades. Scientists realize that there is significant overlap in interests between the solar and space physics community and the human spaceflight community and that the space physics community can assist the goals of the Vision for Space Exploration.

UNDERSTANDING OF SOLAR PHYSICS

The understanding of solar activity and its relation to coronal mass ejections (CMEs) and flares has made tremendous progress on the basis of the contributions of a series of spacecraft, such as Yohkoh, the Solar and Heliospheric Observatory, and most recently the Ramati High Energy Solar Spectrographic Imager. Emerging technologies developed for heliosesimology have shown their ability to forecast active regions before they come around the solar limb. This allows predictive power for large solar active regions, which are the source of most of the strongest flares and the fastest, most hazardous CMEs. These helioseismological techniques are currently implemented and perfected to allow following active regions throughout the entire solar rotation.

There are other observational techniques that are being implemented, many of them in early stages of development. They involve global measures of the free magnetic field before eruptions, the total transport of magnetic-free energy through the photosphere on all relevant temporal scales, and the identification of coronal morphology changes up to 1 day before eruption, for example, through the identification of coronal density enhancement.

Major progress in the predictive capabilities is expected to come from a number of parallel thrusts, which were addressed during this workshop. For example:

- An improvement of observations of the boundary conditions in the corona; this improvement can include "force-free" vector magnetograms in the chromosphere or the corona;
- The assimilation of data to the global coronal magnetic-field specification from radio, x-ray/extreme ultraviolet radiation, and imaging spectroscopy, as well as coronal seismology;
- Detailed observational determination of the magnetic topology in filament channels to determine the CME eruption mechanism; and
- The development of self-consistent magnetohydrodynamic models that couple the photosphere and the corona, with a vigorous investigation of CME initiation processes.

FUNDAMENTAL UNDERSTANDING OF HELIOPHYSICS

There are currently over a dozen NASA, National Oceanic and Atmospheric Administration (NOAA), and Department of Defense (DOD) spacecraft obtaining scientific measurements of solar wind, energetic particles, magnetic fields, and electromagnetic radiation from many vantage points in the heliosphere. They provide data to test and guide the development of theoretical models as well as supporting the operational space weather community. These spacecraft are located at strategic vantage points in the heliosphere from the L1 Lagrange point (1.5 million km upstream from Earth), to inside Earth's magnetosphere, and out to the termination shock (near the boundary with the interstellar medium where the solar wind slows down from supersonic to subsonic speeds).

Current operational space weather models are climatological and empirically based and therefore do badly in predicting extreme events. Several physics-based models in the research community were presented at the workshop. While continuing to provide insight into the understanding of the fundamental processes, research models have too many unknown input parameters for making the required space weather predictions. The challenge to the research community is to know how improved physics can be included in these models without making them too difficult for transition to operational use.

Progress can be made through the vigorous development of models that can describe the following processes: (1) flare/CME/shock initiation, (2) particle acceleration at or close to the Sun, (3) three-dimensional transport in the heliosphere, and (4) particle acceleration near 1 AU (for lunar exploration sites). New observations from current and future space missions will also be needed to provide inputs for testing and validating these models. Finally, the models and missions that provide the input data need to be transitioned to operational use.

SOLAR ENERGETIC PARTICLE EVENT PREDICTIONS AND FORECAST PROSPECTS

The limits of the long-term variability in the space radiation environment need to be determined, including those for galactic cosmic radiation (GCR), solar energetic particle (SEP) events, and Earth's trapped radiation belts. The goal, to predict this variability, may require an understanding of the long-term secular changes in the GCR spectrum using ^{10}Be concentrations measured in ice cores, Voyager measurements beyond the termination shock, nitrate measurements from ice cores, and other historical data. ^{10}Be measurements show that the recent experience of researchers with solar-cycle modulation of GCRs might not be a good predictor of future levels. There are also indications that the current levels of GCR intensity are among the lowest for the past 1,150 years, and that the frequency of occurrence of large solar particle events in recent times has been low compared to the long-term average.

The greatest needs in the area of SEP events, as reported by personnel from the Space Radiation Analysis Group at the NASA Johnson Space Center, are these:

1. Predictions of the temporal evolution profile of the next most likely SEP event at selected energies with associated probabilities, before particles begin to arrive;
2. Flux data from the actual event at the selected energies in real time;
3. The capability to refine the temporal profiles and associated probabilities as the data arrive in real time; and
4. Reliable forecasts of no solar activity of interest, that is, all-clear forecasts.

LONG-TIMESCALE CHANGES IN GALACTIC COSMIC RADIATION

Given the significant contribution of GCR to the total astronaut radiation exposure, it is important to understand long-timescale (decades or more) variations in the GCR. It is well established that at short timescales (months to years) the GCR flux varies with solar activity, peaking at solar minimum (Figure 4.1). Over longer timescales, the solar-cycle amplitudes also vary—some solar maxima are more intense than others. During a period known as the Maunder minimum, sunspots, a measure of solar activity, almost disappeared. Recent solar cycles have had relatively large amplitudes, suggesting that the present is in a period of relatively low GCR maxima. Since a human Mars mission may not happen for several decades, it is important to develop an understanding of how much solar activity may vary from what was experienced over the past few solar cycles, and what these variations may mean to the GCR environment to which astronauts will be exposed. Fortunately there is experimental access to records that shed some light on

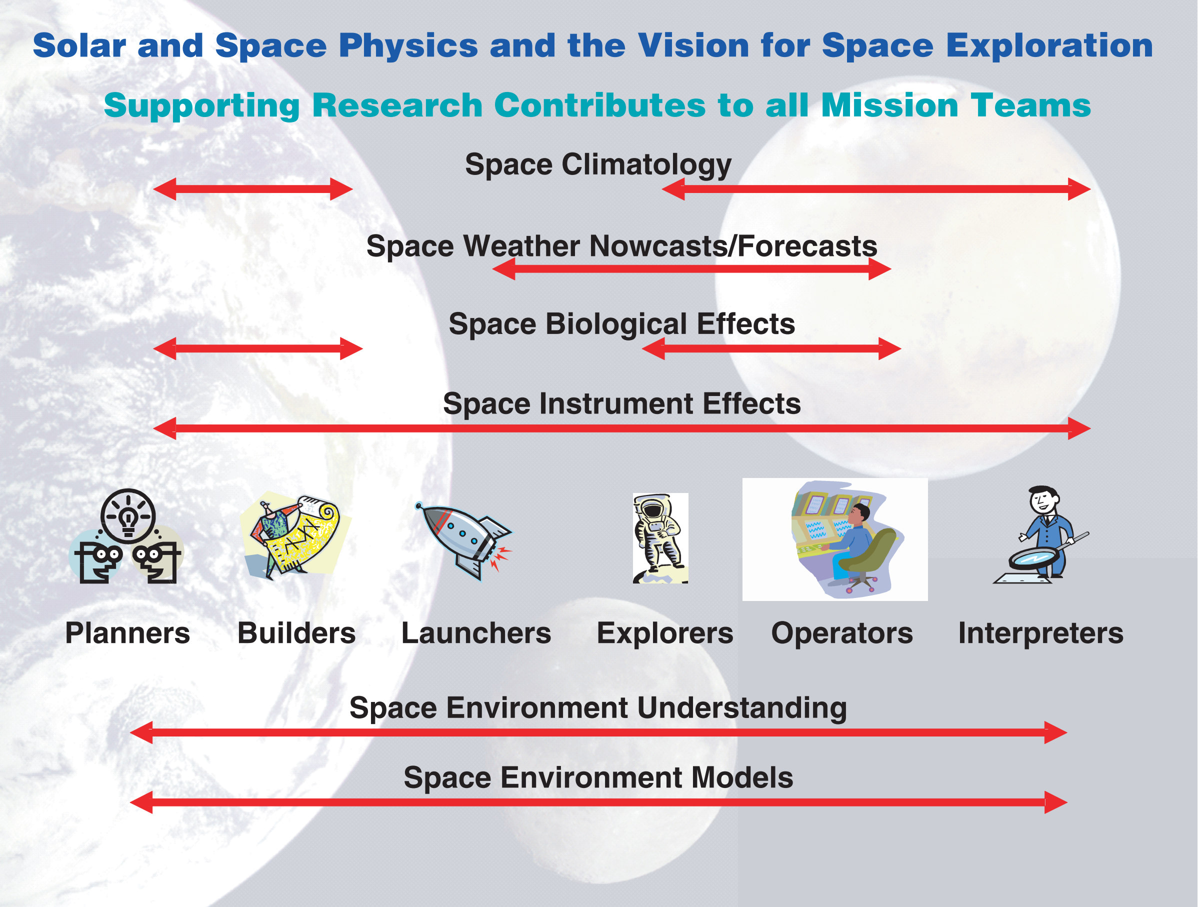

FIGURE 4.1 Solar and space physics research contributes to all aspects of the Vision for Space Exploration. SOURCE: Courtesy of Howard Singer, National Oceanic and Atmospheric Administration Space Environment Center.

long-scale variations of solar activity, including ^{14}C records in tree rings, nitrate and ^{10}Be deposits in polar ice, and even studies of radioisotopes in lunar rocks. Further analysis of these resources could lead to a better understanding of how intense GCR flux could be for future missions.

WORST-CASE SOLAR PARTICLE EVENTS

The studies used to determine long-scale variability in the GCR can also be used to address a related question of high significance to astronauts, which is, How bad can an SEP event be? Knowing how intense an SEP event could be is important to mission design and also to the development of surface operations concepts. There exist only a few decades of direct observation of SEP events, and so only a few major storms such as the August 1972 event have been measured. In order to provide mission planners with guidelines for "worst case" events, the community frequently chooses multiples of a well-known large event (say, two times more intense than August 1972) or uses the spectral character of one event (the very hard 1956 event) and the flux history of another (the large and relatively rapid August 1972 event). A detailed evaluation of historical records may place upper limits on how intense a “superstorm” could be, or at least on what the largest such storm could have been within the past few hundred years.

SUMMARY

In summary, the Workshop on Space Radiation Hazards and the Vision for Space Exploration revealed the numerous ways in which solar and space physics research can contribute to all phases and aspects of the VSE. These contributions are illustrated schematically in Figure 4.1. The VSE will engage teams responsible for planning missions (Planners); for building instruments, habitats, and spacecraft (Builders); for launching vehicles (Launchers); for flying the missions (Explorers); for providing support for mission operations (Operators); and for analyzing a wealth of data and information (Interpreters). Each of these teams and activities will rely on a foundation of knowledge and tools that can be found in space environment understanding and models contributed by solar and space physics research. The figure also illustrates that some solar and space physics expertise will provide critical knowledge to specific mission activities. For example, space weather forecasting will be most important for activities carried out by explorers and operators, whereas space climatology will be more important for planners and builders. In conclusion, solar and space physics provides a rich foundation of space environment information and a community that can be called on to contribute importantly to the success of the Vision for Space Exploration.

Appendixes

A

Reports of the Working Groups

WORKING GROUP A
PREDICTION ON TIMESCALES OF YEARS TO DECADES AND SOLAR-CYCLE VARIABILITY

The focus of Working Group A was to understand the issues involved in predicting long-term solar cycle variability over timescales of years to decades. Ultimately, levels of solar activity and magnetic variations of the Sun control the fluxes of solar energetic particles (SEPs) and galactic cosmic rays that are of key importance for human and robotic exploration of the Moon, Mars, and beyond.

Current Assets—Observations and Models

Sunspot number is well correlated with several other measures of solar activity, including sunspot area, 10.7 cm radio flux, x-ray flares, total irradiance, the geomagnetic aa index, and cosmic ray flux. The long record of sunspot number helps in the characterization of features of past solar cycles. Feature-recognition techniques may help to better characterize magnetic structures on the Sun. This ability could, in turn, lead to the prediction of activity levels with a lead time of several years. Cycle 23 was accurately predicted using a curve-fitting technique that used the cycle properties for the first year or two from the prior solar minimum. Thus, this type of technique can give several-year forecasting capability once a given cycle is under way.

Dynamo models that incorporate deep meridional flow throughout the convection zone to transport magnetic flux (so-called flux-transport models) may have considerable predictive capability. These models transport flux toward the solar equator at the base of the convection zone. It is known that magnetic-field maps show the equatorward drift of active regions, Hale's polarity law, differential solar rotation, and poleward meridional flow. "Magnetic persistence," or the duration of the Sun's memory of its own magnetic field, can be controlled by meridional circulation in the solar convection zone.

There is a flux-transport, dynamo-based prediction scheme for solar activity. It describes the poloidal source on the basis of sunspot areas. In other words, the time variation of the poloidal source function within each sunspot cycle is derived from observations of the sunspot areas during that cycle. A predictive model using this technique is able to correctly predict the sequence of sunspots (and sunspot peaks) for cycles 16 through 23. The method uses cycles 12 through 15 to model and simulate the Sun's memory of its own magnetic-field history.

Based on the successful simulations of cycles 16 through 23, recent work has predicted the strength of cycle 24. This physics-based (i.e., dynamo-based) prediction gives a peak amplitude of cycle 24 that is 1.2 to 1.5 times larger than that of cycle 23. If true, this predicted cycle amplitude would make cycle 24 the largest since cycle 19 (which occurred right at the beginning of the Space Age in about 1960). This physics-based prediction is in contrast to recent predictions made using so-called precursor methods. The precursor methods have uncertainty that decreases as the cycle approaches closer to its peak. By contrast, flux-transport dynamo-model-based predictions use the Sun's magnetic memory, whose duration is controlled by the meridional circulation and magnetic diffusion. This class of solar dynamo model may also have some skill in predicting cycle amplitude two cycles ahead and therefore may be able to predict the amplitude of cycle 25.

The speed of movement of the latitude of sunspot appearance toward the equator as the solar cycle advances is anticorrelated with sunspot cycle period (Hathaway et al., 2003). That is, the faster the drift rate, the shorter the period. Flux-transport dynamo models show similar behavior. The equatorward drift velocity of a cycle is correlated with the amplitude of the second following cycle, a property also seen in flux-transport dynamos with deep meridional circulation. This fact supports the possibility of predicting cycle amplitudes two cycles ahead. This correlation predicts that cycle 24 will be larger than average amplitude, and cycle 25 will be significantly smaller than average amplitude. This prediction is at odds with previous forecasts that have predicted that cycle 24 would be smaller in intensity.

Other key evidence about long-term solar activity and radiation hazards comes from ice core records of nitrates and ^{10}Be. For example, the highest nitrate (NO_y) density in the ice core records from Greenland over the past several hundred years was associated with a large solar event in 1859 (the so-called Carrington solar flare event). The ice core record shows that solar particle events can occur at any time during the 11 year solar activity cycle, but there is evidence that solar particle event peak intensities have been somewhat lower in recent times than they were in the late 19th century. This raises questions about whether the present is a relatively benign period for deleterious radiation. If so, how long will this condition last?

Distributions of solar particle events over the past five cycles have shown that SEPs roughly follow the sunspot number, but there tend to be proportionately more SEPs late in each cycle. There is a very significant variation from cycle to cycle.

What Is Not Known Now But Needs to Be Known for the Vision for Space Exploration?

The human spaceflight missions that will take place as part of the Vision for Space Exploration (VSE) require substantial advance planning (under current plans the Moon landing will not take place until approximately 2018, and the human exploration of Mars has been predicted as taking place no sooner than 25 to 30 years from now). Therefore, the ability to make longer-term predictions of solar-cycle activity is important. Will the radiation environment be significantly different in 2018 than it is today? Will it be different in 2035 compared to that of today? The answers to those questions will affect planning (for instance, when to launch crews) and spacecraft and mission design—for example, the amount of shielding that will have to be provided to protect the astronauts.

Spacecraft are currently designed on the basis of an understanding and expectation of radiation levels that historical ice core data indicate could be abnormally low. If those levels increase to a more commonly occurring level, then the design of spacecraft will also have to change to accommodate them.

How Do Scientists Address the Identified Needs?

It is known that large solar particle events have occurred in the past. However, scientists need to characterize these events better. This can be accomplished through further investigation of ice core data. Also, ^{10}Be measurements show that the recent experience with solar-cycle modulation of galactic cosmic radiation may not be a good predictor of future levels. Better calibration of ice core data vis-à-vis neutron monitor data needs to be obtained.

Reference

Hathaway, D.H., D. Nandy, R.M. Wilson, and E.J. Reichmann. 2003. Evidence that a deep meridional flow sets the sunspot cycle period. *Astrophys. J.* 589:665.

WORKING GROUP B
SOLAR ACTIVE REGIONS, FLARES, AND CORONAL MASS EJECTIONS

The focus of Working Group B was to understand the relationship between solar phenomena that lead to particle acceleration, solar flares, and coronal mass ejections (CMEs), and the solar activity observed on the disk. Active regions, the concentrated magnetic-field configurations that result in plage, sunspots, and bright x-ray emission, also provide the energy source for the most powerful solar flares and CMEs. Active regions form over a period of days and typically live for weeks to months. Some regions appear to be especially dangerous from a space weather perspective, while others do not. Any capability for predicting solar drivers for space weather on timescales ranging from hours to weeks must characterize dangerous active regions. Long-time prediction capability, such as that needed for operational planning of long-duration missions outside of Earth's magnetosphere, critically depends on scientists' ability to enhance the predictive power based on currently available data, model development for flare and CME generation, and novel predictive schemes that involve subsurface analysis through helioseismology, and accurate determinations of the full three-dimensional structure of the solar magnetic field.

Current Assets—Observations and Models

The understanding of solar activity and its relation to CMEs and flares has made tremendous progress based on the contributions of a series of spacecraft, such as Yohkoh, the Solar and Heliospheric Observatory (SOHO), and most recently the Ramati High Energy Solar Spectrographic Imager (RHESSI). Furthermore, in situ data of CMEs and their global structure, such as from the Advanced Composition Explorer (ACE), WIND, and Ulysses, have provided important constraints for the understanding of these ejecta and their evolution in the structured heliosphere. Magnetic flux is entering the solar atmosphere everywhere on the disk, through the emergence of so-called ephemeral regions. These bipolar structures emerge at a rate that allows replenishment of the entire solar magnetic field within a timescale of 40 hours or less. In addition, large-scale strong fields are emerging, with large temporal and spatial dependence. These active regions are more localized and dominate the local structure of the local solar atmosphere. The relation of these two sources of magnetic flux, and their relation to the thermodynamics of the corona, and the occurrence of flares and CMEs are still subject to the active research of a sizable community that was represented in this working group.

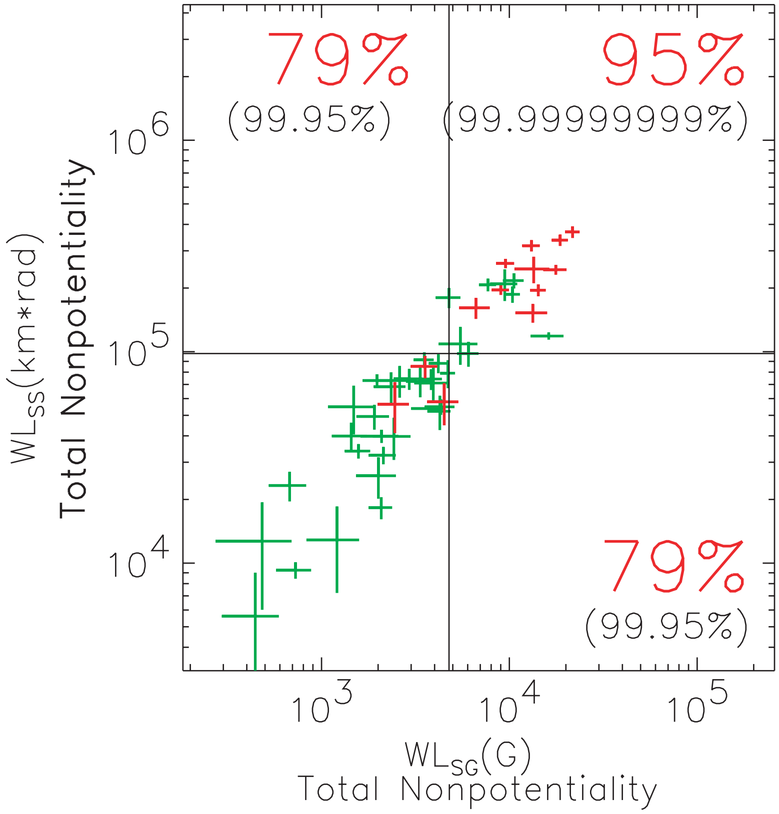

FIGURE A.1 Vector-magnetogram-based predictions of coronal mass ejections. Red symbols indicate active regions that lead to eruptions within a certain time period, and green symbols indicate active regions without eruptions. The vertical axis shows values for the total shear-weighted length, L_SS, of strong shear regions along the main neutral line (in units of radians*km). The horizontal axis shows values for the total gradient-weighted length, L_SG, of strong magnetic gradient regions along the neutral line (in units of G). SOURCE: Courtesy of D.A. Falconer, University of Alabama, Huntsville. (See also Falconer et al., 2002.)

Observational

Most investigations attempting to relate the evolution of the solar photospheric magnetic field and its coronal responses still rely on the measurement of a single component, along the Sun-Earth line. Owing to the highly nonpotential character of source regions giving rise to flares and CMEs, extrapolations to full three-dimensional field topologies, their reconnection geometries, and currents are almost impossible. Owing to the available vector magnetic-field data of strong field regions, new empirical predictors have become available, as shown in Figure A.1. Owing to the evolutionary behavior of the photospheric magnetic field on many timescales, the accurate prediction of the time of a flare/CME event is still not possible.

Emerging technologies developed for heliosesimology have shown their ability to forecast active regions before these regions come around the solar limb. This allows predictive power for large solar active regions, which are the source of most of the strongest flares and the fastest, most hazardous CMEs. These helioseismological techniques are currently implemented and perfected to allow following active regions throughout the entire solar rotation.

There are other observational techniques that are being implemented, many of them in early stages of development. They involve global measures of the free magnetic field before eruptions, the total transport of magnetic-free energy through the photosphere on all relevant temporal scales, and the identification of coronal morphology changes up to 1 day before eruption, for example, through the identification of coronal density enhancement.

Modeling

Modeling of the photosphere coronal interfaces falls within two major sets of models. The first set is fundamentally time-stationary and focuses on the overall topology of magnetic fields with simplifying assumptions, such as force-free assumptions, or potential field assumptions. These models have been successfully used to analyze the overall magnetic structure of active regions, and the corona as a global entity. However, these models are not useful for developing predictions for the timing of eruptions, or even the overall topology of CMEs.

Secondly, there is a set of CME initiation models that seek to establish the linkage between photospheric forcing and eruptions (Klimchuk, 2001). These models have been limited by computational technologies owing to the necessity of describing, simultaneously, the small-scale reconnection process and the global-scale CME eruption. There has been important progress in these fields, with a number of candidate models becoming available that can lead to testable predictions. These models are far from applications in a predictive environment, such as would be useful for the Space Environment Center of the National Oceanic and Atmospheric Administration (NOAA).

What Is Not Known Now But Needs to Be Known for the Vision for Space Exploration?

As part of the Vision for Space Exploration, NASA seeks to establish a human presence on the Moon for short (days to weeks) and long-term (weeks to months) stays. For such a trip, there is an operational need to predict solar eruptions and their effects for particle acceleration (addressed by Working Group C).

For any prediction capability exceeding 2 days, the physical processes addressed by this working group become crucial. The workshop participants identified the following important issues that need to be addressed by future observational and modeling efforts. It is clear from these questions that this research is very much exploratory. Predictive schemes should not be expected very soon.

- How accurately can the coronal magnetic field now be characterized in three dimensions, and how much better will this be with future data-gathering capabilities?
- The physics of CME initiation is only poorly understood. How can the most effective progress in the scientific understanding of CME initiation be made?
- To what extent can CME initiation be predicted without detailed understanding of the CME initiation physics? (I.e., what is the usefulness of empirical and statistical tools?)
- The most dangerous space weather events can be traced back to active regions with “dangerous” (e.g., delta-spot) configurations. What are the physical mechanisms that lead to such active region configurations? Can these mechanisms be predicted?
- To what extent is it possible to predict the emergence of active regions before they reach the photosphere, or to predict the rotation of an active region from behind the limb?

- To what extent does the pre-event corona allow scientists to predict eruption owing to new emergence?
- Is it possible to predict significant long-term changes in the flux of galactic cosmic rays caused by changes at the Sun propagating out into the large-scale heliosphere?

How Do Scientists Address the Identified Needs?

Major progress in the predictive capabilities is expected to come from a number of parallel thrusts, which were addressed during this workshop. For example:

- An improvement of observations of the boundary conditions in the corona; this improvement can include “force-free” vector magnetograms in the chromosphere or the corona;
- The assimilation of data to the global coronal magnetic-field specification from radio, x-ray/extreme ultraviolet radiation and imaging spectroscopy, as well as coronal seismology;
- Detailed observational determination of the magnetic topology in filament channels to determine the CME eruption mechanism; and
- The development of self-consistent magnetohydrodynamic models that couple the photosphere and the corona, with a vigorous investigation of CME initiation processes.

These efforts are expected to benefit from upcoming missions and programs (see the list in the following report, by Working Group C). These investments will be best exploited if they are coupled with comprehensive modeling efforts. These models need to establish connections between different kinds of observations of solar eruptions, combining remote imaging and spectroscopy and in situ ground-truth measurements of CMEs.

References

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Klimchuk, J.A. 2001. Theory of coronal mass ejections. P. 143 in *Space Weather* (P. Song, H.J. Singer, and G.L. Siscoe, eds.), AGU Monograph 125, AGU Code GM1259841. American Geophysical Union, Washington, D.C.

WORKING GROUP C
PROPAGATION OF EVENTS IN PROGRESS

The focus of Working Group C was on understanding the propagation and evolution of solar energetic particles. SEPs are a potentially serious risk to humans and their sensitive instruments when they journey beyond Earth’s protective magnetosphere to reach the Moon and other locations called for in the Vision for Space Exploration. From a science standpoint, it is important to understand the variability and extreme values for properties of SEP events in order to develop a predictive capability that could eventually be incorporated into an operational space weather warning system. The science community recognizes that an accurate and reliable warning system requires a better understanding of the physical processes that produce SEP events. A firm foundation for such a system requires the development of physical models for particle production, acceleration, and transport. These models should be validated by appropriate observations before they are transitioned to operational use.

Current Assets—Observations and Models

There are currently more than a dozen NASA spacecraft obtaining scientific measurements of solar wind, energetic particles, magnetic fields, and electromagnetic radiation from many vantage points in the heliosphere. They provide data to test and guide the development of theoretical models as well as supporting the operational space weather community. The supporting NASA operating missions include ACE, Cluster, Fast Auroral Snapshot Explorer, Geotail, IMAGE, Polar, Ramati High Energy Solar Spectrographic Imager (RHESSI), Solar and Heliospheric Observatory (SOHO), Thermosphere Ionosphere Mesosphere Energetics and Dynamics mission (TIMED), Transition Region and Coronal Explorer (TRACE), Ulysses, Voyagers 1 and 2, and WIND. These spacecraft are located at strategic vantage points in the heliosphere from the L1 Lagrange point (1.5 million km upstream from Earth), to inside Earth's magnetosphere, and out to the termination shock (near the boundary with interstellar medium where the solar wind slows down from supersonic to subsonic speeds). Spacecraft missions from other agencies (NOAA and DOD) also provide valuable data for inputs to space weather models.

Current space weather models are climatological and empirically based and therefore do badly in predicting extreme events. Two well-known types of models are the ones used by (1) the Air Force Weather Agency (AFWA), which triggers on x-ray or microwave emission from flares; and (2) the NOAA SEC, which triggers on Geostationary Operational Environmental Satellite (GOES) x-ray data. NOAA supports NASA's Space Radiation Analysis Group (SRAG) in its forecasts for the International Space Station (ISS). The AFWA models are only accurate to an order of magnitude in the estimates for peak flux and can estimate the timing of the maximum flux (to within about 2 hours after onset).

There are many physics-based models in the research community. Those presented at the workshop are being developed at the Boston University Center of Integrated Space Weather Modeling, the University of California (Berkeley and Riverside), the Johns Hopkins University Applied Physics Laboratory, and the University of Michigan. The challenge to the research community is to know how improved physics can be included in these models without making them too difficult for transitioning to operational use.

What Is Not Known Now But Needs to Be Known for the Vision for Space Exploration?

The first major goal of the Vision for Space Exploration is to establish a human presence on the Moon for short-term (days to weeks) and long-term (weeks to months) stays. For such a trip the primary radiation danger is from acute exposure from high-energy particles emitted by solar flares and coronal mass ejection shocks. Important quantities that space weather modelers need for better forecasting of SEP events are the following: (1) the onset time for an SEP event, (2) its time-intensity profile, (3) the "spectral indices" of the energy spectrum, (4) the shock arrival time, and (5) the anisotropy in the particle velocity distribution (lower priority). For the near-term need, it would be very helpful to be able to predict, with high assurance, "all-clear" periods when there is a very low probability of an SEP event expected.

Table A.1 shows the energetic particles and their energies of most interest to astronaut safety and preventing hardware disruption or damage.

TABLE A.1 Energetic Particles and Their Energies of Most Relevance to the Vision for Space Exploration

Application	Ion Species	Particle Energies
Astronaut safety	H, He, heavy ions	>10 MeV per nucleon
Dosimetry	e	>1 MeV
Hardware systems	H, He, e, plus heavy ions	Greater than a few MeV per nucleon

The workshop participants identified the following important issues that need to be addressed by future observational and modeling efforts:

- Why does the time evolution of large SEP events show a great deal of variability in such features as the initial rise of intensity, time of maximum intensity, and decay time?
- Why do the maximum intensities and distributions of particles (with different energies, masses, and ionization states) vary widely?
- What are the effects of overlapping, multiple events, which often happen during the most active periods?
- How does the passage of an interplanetary shock at Earth orbit increase the SEP intensity?

How Do Scientists Address the Identified Needs?

The consensus of Working Group C is that present operational models are too simplistic, while research models have too many unknown input parameters for making the required space weather predictions. Progress can be made through the vigorous development of models that can describe the following processes: (1) flare/CME/shock initiation, (2) particle acceleration at or close to the Sun, (3) three-dimensional transport in heliosphere, and (4) particle acceleration near 1 AU (for lunar exploration sites). New observations from current and future space missions will also be needed to provide inputs for testing and validating of these models. Finally, the models and missions that provide the input data need to be transitioned to operational use.

Present one- and two-dimensional models of CME propagation and shock acceleration need to be extended to full three-dimensional models that can model the global structure of the heliosphere from the Sun to 1 AU and beyond. Some success in modeling shock-accelerated SEPs has been made with quasi-parallel and quasi-perpendicular shock models, but these models cannot yet model specific events (e.g., Zank et al. [2000]). Better understanding of how the magnetic field geometry, shock speed, seed particle population, and interplanetary transport affect the SEP output (energy spectra, fluence, intensity profile, maximum energies, and velocity anisotropies) are still needed. Also, some SEPs may be produced in compression regions without a shock and by current sheets in flares and CMEs. Realistic models for these types of events are also needed.

Progress in model improvement requires the systematic validation of models against large numbers of past and future events. The Living With a Star Targeted Research and Technology program could encourage this sort of testing by making such validation efforts one of the program's focus areas. Currently, it is difficult to validate models because the available data are spotty. In other cases, the required data at the inner boundary conditions near the Sun do not yet exist. What is required are accurate solar wind and magnetic-field parameters at the inner boundary near the Sun and at locations of interest to the VSE. The models are then required to forecast conditions based on these inputs at the coronal boundary.

Some current missions have demonstrated the types of new measurements that are required. RHESSI observations indicate some important differences in the source regions for electrons and ions in solar flares. Recent SOHO Ultraviolet Spectroscopic Coronagraph observations demonstrate how CME shock parameters (including information on suprathermal seed particles) can be obtained in coronal regions within a few solar radii of the Sun. Ground-based radio observations of Type-II radio bursts can reveal information about the magnetic fields and temperatures within CME shocks that produce energetic particles. Knowledge of the turbulence spectrum in the corona and solar wind is another key input. Many models for predicting SEPs that are currently under development can benefit by using these types of data to validate their results.

In situ measurements from the ACE and WIND provide much of the ground-truth data needed to test SEP acceleration models. However, currently there are no funds identified in NASA's long-range plan for follow-on missions.

Planned near-term facilities and missions will provide the new diagnostics for obtaining better information about conditions at the Sun before and during eruptive events:

- *Advanced Technology Solar Telescope (ATST)* will provide routine high-cadence, ultrahigh-resolution measurements of active region magnetic fields.
- *Frequency Agile Solar Radio (FASR) telescope array* will provide high-resolution, full-Sun images of coronal shocks and other SEP sources.
- *Solar Dynamics Observatory (SDO)* will have a 10-sec cadence for measurements of magnetic fields, coronal x-rays, and ultraviolet emission to provide a better understanding of CME and flare source regions.
- *Solar Terrestrial Relations Observatory (STEREO)* will provide three-dimensional views of CMEs and measure associated particles and fields from two spacecraft locations.
- *The Japanese-U.S. Solar-B mission* will obtain routine vector magnetic-field measurements of CME and flare initiation sites on the Sun.

New missions that have yet to start their hardware development phases are also vital:

- *Inner Heliosphere Sentinels* will fly multiple spacecraft to better understand the evolution of solar disturbances from 0.25 AU out to beyond Earth's orbit.
- *Solar Probe* will investigate the only unexplored region of the heliosphere from 4 to 30 solar radii to measure particles and fields at SEP source regions.
- *The European Space Agency's Solar Orbiter* will make the first high-inclination measurements of the Sun and solar wind from a near-Sun location (0.21 AU).

Other future mission concepts that could provide space weather warning to locations that are far from the Earth-Sun line are the multispacecraft Solar Weather Buoys stationed at 0.9 AU, the Mars Aeronomy Orbiter stationed at Mars, and the Interstellar Probe at our solar system's outer boundary.

To summarize, the heliophysics community recognizes its responsibility to contribute in a timely manner to the Vision for Space Exploration by engaging in the following activities:

- Improving basic understanding of governing physical processes of the space radiation environment;
- Developing models that can form the basis of greatly improved predictive models;
- Validating these models with improved observations;
- Developing the conceptual and hardware infrastructure for an operational space weather system; and
- Carrying out exciting exploratory missions such as those recommended by the 2005 NASA Roadmaps and the NRC (2002) decadal survey, *The Sun to the Earth—and Beyond*.

References

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WORKING GROUP D
EARTH, LUNAR, AND PLANETARY (MARS) ENVIRONMENTS

Working Group D focused on how the space environments around the Moon and Mars are impacted by space weather. It discussed extreme events, including the effects of SEPs. Discussions started with basic scenarios and concepts and progressed to the identification and uses of existing data, currently planned measurements, and the identification of additional new measurements necessary to resolve key unknowns. The group also addressed lessons learned from the study of Earth's upper atmosphere and ionosphere concerning solar-activity-related disturbances that could affect Mars exploration. The group then asked what is currently known, what is not known and needs to be known for the Vision for Space Exploration, and how those issues could be addressed. Each of these questions was considered for the Earth environment, lunar orbit and surface, and Mars orbit and surface.

Earth Environment

Because of its importance to understanding and mitigating the impacts of space weather on and near Earth, Earth's environment is an area in which many scientists are conducting ongoing research.

There are models of the interaction of Earth's magnetosphere with the surrounding plasmas and fields of the heliosphere. There are standard models of the low-Earth-orbit, geosynchronous radiation belt with solar-cycle variations, a history of SEP observations and impact studies, models of space radiation effects on satellite systems in this environment, and an extensive archive of science data and space systems anomalies.

Closer to Earth, there are standard operational models of the ionosphere and upper atmosphere. Most of these empirically include the effects of solar and geomagnetic activity, but generally through surrogate parameters (extreme ultraviolet [EUV] radiation or radio flux or magnetic fluctuations measures at locations on the surface of Earth). There are archives of ground- and space-based observations. There are archives of documented impacts on communications and satellite operations.

Much remains to be done to improve the understanding of Earth's environment as a system. In each domain there is a need to better understand and dynamically model the magnetosphere, the radiation belts, and the ionosphere, especially during periods of extreme events. The models need to transition from statistical and climatological models to truly predictive models. The magnetosphere needs to be coupled through physics-based global models to the surrounding heliosphere. The radiation belts and ionosphere need to be more intimately coupled to influences of changes in the heliosphere, including during periods of solar activity and increased flux of energetic particles.

Suggestions on how to proceed, raised during the working group's breakout session, included the following:

- Provide the necessary data-mining infrastructure, together with new observations targeted toward this goal, for both model parameterization and validation (note: using these effectively requires solar and upstream interplanetary supporting information);
- Use Earth high-latitude upper atmosphere as a local "laboratory" for Mars (to investigate matters from atmospheric transport code validations with balloon experiments, to studying responses of a thin atmosphere, to solar photon and particle inputs expected at Mars); and
- Collaborate on and cooperate in and sponsor joint studies and investigations with like-minded programs with similar goals—especially the Living With a Star program.

Lunar Environment (Orbit and Surface)

A significant amount of information on the lunar environment (surface and orbital) exists from past relevant observations by Explorer 35, Apollo, Clementine, Lunar Prospector, Geotail, and WIND spacecraft.

The existing data provide insight into the lunar plasma and field environment, crustal magnetic fields, lunar surface charging, dust, lunar atmosphere (also remote detections), SEP events, and dosimetry at the Moon. There is surface neutron information from Lunar Prospector, plus surface neutron models (Space Ionizing Radiation Environments and Shielding Tools [SIREST] transport codes and others). There is also relevant surface composition information from Clementine, Lunar Prospector, and the archive of lunar samples. Some information about the lunar radiation exposure history has been derived from lunar samples.

There are still gaps in understanding of the lunar environment. There is also concern that the available information is not sufficiently comprehensive or adequately validated, either on the lunar surface or in lunar orbit, to meet the needs of the VSE.

One such gap addressed by the working group was the issue of electrostatic charging on the lunar surface. The temporal dynamics of surface electrostatics, particularly at dawn and dusk, and the spatial variability of surface charging, and how it varies with lunar geology are not well understood.

The working group also observed that the steady-state description of the lunar environment may be inadequate during periods when the Moon transits Earth's magnetotail. This occurs in the middle of the lunar day on the Earth facing side, so it is likely that astronaut activities will be under way under transit conditions.

Suggestions on how to proceed, raised during the breakout session, included the following:

- Restore (as necessary) existing lunar environment data (including those from Apollo and Clementine). Convene a splinter group to revisit these and all existing environment data relevant to the Vision for Space Exploration from all sources—to reestablish the environment knowledge base;
- Install more-comprehensive lunar surface models in surface radiation environment codes;
- Determine (now) whether Lunar Reconnaissance Orbiter measurements will sufficiently validate models of the radiation environment in orbit and on the surface. Determine what further orbital and surface measurements are needed (e.g., neutron, dust, electric-field measurements on the Lunar Robotic Lander) to establish environment knowledge for human expeditions; and
- The working group emphasized the importance of the Lunar Reconnaissance Orbiter and a subsequent lunar lander to aid in understanding the space environment.

Mars Environment (Orbit and Surface)

Properties of the primary galactic cosmic radiation (GCR) and SEP environment are generally extrapolated from observations near Earth and from several deep space missions. The GCR flux increases by radial distance from the Sun to a degree that is generally understood. The secondary particles generated by collisions between the primary particles and the atmosphere and surface of Mars have been estimated by standard transport codes (e.g., SIREST, which requires other surface and atmosphere models).

In spite of the number of spacecraft that have been sent to Mars, there have been no comprehensive measurements of the radiation environment in Mars orbit and on the martian surface. Direct on-orbit measures of a portion of the neutron flux and energetic protons in a limited energy range have been made by instruments on Odyssey and inferred indirectly from instruments on Mars Global Surveyor.

Surface radiation calculations have been performed for Earth's Moon, Mars, and Callisto. These calculations show that radiation shielding will be an important consideration in the planning of long-term missions to these surfaces. These calculations also demonstrate the large variation in exposure rates due to solar cycle.

Previous and new measurements show dynamic, structured, variable ionosphere and upper-atmosphere systems (depending on season, dust, crustal magnetic fields, solar EUV flux, solar wind conditions, and so on). Some models exist: global circulation models and thermospheric global circulation models for lower and upper atmosphere, and more limited ionosphere models. Upper-atmosphere models are used in Mars mission aerobraking plans.

The main missing element for the radiation environment is a validation of orbital and surface radiation models and transport codes, for both spectrally hard (GCR) and softer (SEP) components.

Validation is also needed of atmosphere and ionosphere models to be used in applications. Upper-atmosphere models will be used in entry and orbital planning, global dust transport dynamics, and atmospheric shielding against radiation. Ionosphere models will be considered in communications technologies planning. Validation requires supporting solar and interplanetary data together with upper-atmospheric and ionospheric measurements.

Electrostatic properties of the martian surface have been estimated, but good temporal and spatial dynamics models do not exist.

Model validation will be critical to support a "Be there before you get there" paradigm to design system architectures and to simulate VSE situations.

Suggestions on how to proceed, raised during the working group's breakout session, included the following:

- *Validate radiation transport codes, for example, with measurements on stratospheric balloons at Earth and on the martian surface.* There is a need for a science-based review to determine if the planned Mars Science Laboratory measurements are sufficient for the validation of transport codes. If not, what measurements are needed and what instruments are required to make those measurements? It was pointed out that a lack of local, upstream measurement of SEP fluxes and spectra limits transport code validation. Codes need to be validated in both hard and soft spectral ranges. A suggestion was made to consider convening a splinter group to answer this question and to make recommendations. Communication with the exploration and the Mars science communities will be critical to the success of model-validation efforts.
- *Undertake a special initiative to collect and synthesize the full range of available atmospheric and ionospheric measurements relevant to VSE orbiters and landers, and to make model improvements to include all significant parameters (e.g., dust, flare effects, and so on).* This effort would lead to recommendations to make specific on-orbit and surface measurements to validate models in areas of VSE interest, including orbital evolution and craft entry, and on-surface operations (e.g., dust, E and B field effects, ionospheric conditions relevant to communications and operations).
- *Cooperate with and coordinate plans and activities with the Mars Exploration Program where appropriate and advantageous, which is critical.*

Timelines

The working group recognized that some measurements are needed immediately, either because decisions are being made right now in the exploration community (shielding and operations strategies for lunar exploration, for example) or because a long lead time is needed to develop and deploy appropriate sensors on appropriate platforms. The working group prepared a strawman list of near-, mid-, and far-term activities. This list should be used as a starting point and could be the focus of a workshop.

- *Near-term activities:*
  - Updates and upgrades of radiation transport codes;
  - Radiation-transport-codes validation on stratospheric balloons;
  - Lunar data restorations and synthesis activity;
  - Creation of data-mining infrastructures: Earth, Moon, and Mars;
  - Collection and synthesis of Mars atmosphere data specific to VSE needs;
  - Radiation environment and upper-atmosphere/ionosphere model developments based on data mining and ongoing observations.
- *In-process and midterm activities:*
  - Lunar Reconnaissance Orbiter;
  - Mars Science Laboratory;
  - Support of solar and helio missions (Sentinel, SDO, STEREO); and
  - Validation of Earth radiation environment and lunar and Mars surface radiation models.
- *Future or needed study:*
  - Mars upper-atmosphere characterization missions, and
  - Mars upstream solar monitoring or validated models.

Other Comments

The working group discussed additional issues that were felt to be overarching issues, relevant generally to other working groups. In summary, there is a need to acknowledge, learn from, and communicate with the wide range of groups conducting and generating overlapping activities, studies, and reports (e.g., Mars Exploration Program Analysis Group; Living With a Star; other National Research Council committees; the Committee on Space Research of the International Council for Science; the European Space Agency geospace, Mars, and lunar study groups and missions; NASA Roadmap groups; and the astrobiology community). There is concern that the myriad of groups and reports may be confusing or conflicting, or that efforts may be needlessly redundant, or that relevant good ideas, results, and/or opportunities from others may not be folded in to the Vision for Space Exploration and NASA's advantage.

WORKING GROUP E
DOSIMETRY

The focus of Working Group E was to understand the systems and techniques used to measure space radiation and efforts to improve these measurements.

Radiation exposures of humans on crewed missions in low Earth orbit (LEO) have been measured using radiation-detection and dosimetry systems, including thermoluminescent dosimeters, nuclear emulsions, plastic track detectors, charged-particle telescopes, and tissue-equivalent materials, since the early days of space travel. Databases of doses to crews traveling into space during the Mercury, Apollo, Skylab, shuttle, and International Space Station era have been archived. In some cases, the original detector materials are stored and available for reanalysis and further data mining.

Unmanned missions beyond LEO, such as the Interplanetary Monitoring Platform series of missions, the ACE mission at the L1 point, and the recent Odyssey mission to Mars, have at times also carried instruments, such as the Mars Radiation Environment Experiment (MARIE) detector, that have recorded particle fluxes and their associated doses. The latter has recently made measurements in martian orbit, but no measurements of doses or particle fluxes on the surface of Mars exist at present.

Energetic-particle detectors on the GOES series of weather satellites have provided continuous measurements of charged-particle spectra in geostationary orbits for about three decades.

What Is Not Known Now But Needs to Be Known for the Vision for Space Exploration?

For solar energetic particle (SEP) events, predictive tools to enable mission controllers and crews in deep space to make informed operational decisions in real time are needed but are not yet available.

Methods involving artificial intelligence and other predictive techniques, such as Bayesian inference and locally weighted regression, have been investigated and have demonstrated promise in providing nowcasting capabilities after SEP event particles begin to arrive (Hoff et al., 2003; Hines et al., 2005; Neal and Townsend, 2005). These methods are capable of predicting, with reasonable accuracy, total doses and the temporal evolution of the dose as particles arrive very early in the evolution of the event. They are also robust enough to adjust for the arrival of particles associated with interplanetary shocks. However, these methods are presently unable to forecast SEP fluence levels and their associated doses before particles begin to arrive. Hence, they could provide a much-needed capability for mission operations, but in a merely stopgap role. Unfortunately, computer codes implementing these nowcasting models are research codes and not in the form of operational tools that are usable by mission operations personnel.

The greatest needs in the area of SEP events, as reported by personnel from the Space Radiation Analysis Group at the NASA Johnson Space Center, are the following:

- Predictions of the temporal evolution profile of the next most likely SEP event at selected energies with associated probabilities, before particles begin to arrive;
- Flux data from the actual event at the selected energies in real time;
- The capability to refine the temporal profiles and associated probabilities as the data arrive in real time; and
- Reliable forecasts of no solar activity of interest—that is, all-clear forecasts.

Accomplishing the first item of the previous list involves developing methods for forecasting differential fluence rates (particles/cm^2/time/energy) at various times τ before the event begins, that is, $F(E, t, \tau)$ at 1 AU, along the spacecraft trajectory to Mars, and at Mars for the following:

— *Protons (H):*
Parameter ranges:
E (energy): 30, 60, 100, 500, 1,000 MeV
t (time): 5 minute increments from $t = 0$ (SEP event onset) until fluxes return to background levels
τ: 0 (now) and for 3, 6, 12 , and 24 hour lead times.

— *Helium (He):*
Same parameter ranges as above for protons (except now energies are in MeV/n, and the upper bound of interest is cut off at 500 MeV/n).

— *Electrons (e):*
Same parameters as above, except:
E: 0.5 to 5.0 MeV.

The limits of the long-term variability in the space radiation environment need to be determined, including those for GCR, SEP events, and Earth's trapped radiation belts, with a view to prediction. This may require understanding the long-term secular changes in the GCR spectrum using ^{10}Be from ice cores, Voyager measurements beyond the termination shock, nitrate measurements from ice cores, and other historical data.

Dosimetric measurements on lunar and martian surfaces using tissue-equivalent detectors that include both charged-particle and neutron contributions to dose and dose equivalent are needed.

Mechanisms and procedures for transferring knowledge and computer codes from the research realm to the operational realm need to be developed.

How Can Scientists Obtain the Needed Knowledge?

In order to obtain better information, the community must carry out the following:

- *Obtain U.S. access to particle and dose data from missions conducted by other countries that enable addressing the needs mentioned previously.* Monitoring at L1 is preferred because it is outside Earth's magnetosphere, is approximately at 1 AU, and allows for continuous coverage of the deep space radiation environment. Monitoring of charged-particle and neutron radiation fields and associated doses on the lunar and martian surfaces is also needed.
- *Develop a "technology transfer" mechanism for moving research into operational tools for use by mission planners and controllers.*
- *Conduct research that develops methods for reliably forecasting SEP event fluence rates and temporal profiles, and their associated probabilities, with lead times ranging from hours to 1 day, before particles actually begin to arrive from such an event. Methods of forecasting "all-clear" periods also need to be researched and developed.*

References

Hines, J.W., L.W. Townsend, and T.F. Nichols. 2005. SPE dose prediction using locally weighted regression. *Radiat. Prot. Dosim.* 115(1-4):232-235.

Hoff, J.L., L.W. Townsend, and J.W. Hines. 2003. Prediction of energetic solar particle event dose-time profiles using artificial neural networks. *IEEE Trans. Nucl. Sci.* 50(6):2296-2300.

Neal, J.S., and L.W. Townsend. 2005. Multiple solar particle event dose time profile predictions using Bayesian inference. *Radiat. Prot. Dosim.* 115(1-4):38-42.

WORKING GROUP F
EFFECTS ON INSTRUMENTS, SPACECRAFT, AND COMMUNICATIONS

During the intense and long-lasting solar storms in October and November 2003, the so-called Halloween Storms, the MARIE experiment was permanently lost (Barbieri and Mahmot, 2004). Ironically, the purpose of the MARIE experiment was to understand and characterize the radiation environment, not only near Mars and on its surface but also in the interplanetary space between Earth and Mars, in order to plan for future manned spacecraft and missions to Mars. It is almost always difficult to determine with certainty the cause of a spacecraft or instrument failure; however, in addition to the MARIE instrument, a number of other spacecraft and instruments in near-Earth space suffered during the Halloween storms. Fortunately, humans were not dependent on the operation of this instrument, but when humans venture again to the Moon and for the first time on the long voyage to Mars, it will be essential to ensure that difficulties with instruments, spacecraft, and communications do not threaten mission success and human lives. Working Group F addressed these issues.

The meeting description that introduced Working Group F stated: "Solar activity can affect instrumentation, spacecraft and communications in several ways. The solar energetic particle radiation has been found to degrade the performance of solar cells. This radiation may affect the electronics in all kinds of instrumentation primarily by causing single event effects. It can also interfere with various kinds of sensors both by direct ionization and by activation of the sensor or surrounding materials. For example, direct ionization can interfere with the imagery obtained using solid state cameras and may degrade optical and thermal control surfaces. Activation can interfere with gamma ray spectrometers used for scientific investigations. This group will discuss the effects of solar activity on these systems and identify approaches to avoid or mitigate these effects."

Space weather effects on instruments and spacecraft have received much attention in the near-Earth space environment. Among the space environment effects that are of concern for instruments, spacecraft, and communications are these: single-event effects in electronics and sensors, total radiation dose to components, radiation damage to sensors and solar cells, and electrostatic charging. All of these effects are of concern for missions to the Moon and Mars. The working group discussed topics that ranged from test facilities needed for electronic components and systems, to the role of environmental models, to the needs for forecasting and specifying space weather conditions. These topics are discussed below. In addition, the group recognized the value of collecting, preserving, and accessing long-term space weather data sets for design, modeling, and operations activities.

Instruments and equipment that will be used on missions to the Moon and Mars need to be tested for their suitability and robustness in a variety of space environments. These environments include diverse regimes that range from conditions near Earth to interplanetary space, to the Moon and Mars. Instruments and equipment will be exposed to a broad range of particle energies and composition from sources such as galactic cosmic rays, solar energetic particle events, and trapped radiation environments. There is also an expectation that commercial off-the-shelf parts and systems such as personal computers and videocameras will be heavily utilized and will need testing to ensure performance in the disparate environments. Therefore, there is a need for the availability of and access to adequate high-energy particle beams at accelerators for testing and related performance measurements to simulate the space radiation environment under controlled conditions.

NASA engineers have been using various accelerators around the country, but one facility exists where beams of all relevant cosmic ray energies and particle species are available. This is the NASA Space Radiation Laboratory at the Brookhaven National Laboratory. For Vision for Space Exploration projects to gain access to this facility, there is a need for a Memorandum of Understanding between the facility and the VSE program so that proposal-evaluation procedures for using the facility are responsive to VSE engineering activities as well as science investigations. In addition to the need for testing before launch, the group also described the value and importance of on-orbit testing for critical system tests and model validation.

Space environment modeling plays a vital enabling role for missions to the Moon and Mars. At Earth, 1970s vintage, static trapped radiation belt models such as AE8 and AP8 that predict electron and proton flux spectra in Earth's radiation belts are inadequate and outdated. Even the more recent, 1990s Combined Release and Radiation Effects Satellite models are limited because they were based on a very brief interval (about 1 year of data). Updated models that are dynamic, taking into account current solar wind and magnetospheric conditions, are needed to provide the history of variations on timescales that range from solar cycles to minutes.

If Mars mission architecture includes parking a transit vehicle at geosynchronous orbit, it will be necessary to better understand the spacecraft charging environment, including short-term variations at that location. Regarding SEP events, more work is needed to understand the most appropriate models and methods that characterize these conditions, including extreme-event studies, risk-based models, and data-based analysis of long-term records.

Improved models of proton and heavy-ion environments (flux, fluence, and energy spectra) in SEP events are needed because of their effects on systems. Between Earth and Mars, the data on helio-radial dependence of the flux and fluence of SEP events are needed. To better design, protect, and test electronics, new models are needed to better incorporate SEP event conditions and galactic cosmic ray models, including correct solar-cycle modulation of composition. These models need improvements that better address geometry complexity, decreasing feature size, track effects, and single-event transient effects. New physics-based modeling, incorporating particle interactions and device physics, offers improved guidance for design, selection, and protection of devices and instruments.

Real-time knowledge of space weather conditions during flights to the Moon and Mars is important for mission success, but it requires improved observations, modeling, and understanding. Without a doubt, new tools will be needed for forecasting space environmental conditions on Mars missions. Solar particle event occurrence and the expected time profile at the vehicle location are among the most serious environmental conditions to contend with, yet they are also among the most difficult to forecast. For the moment, since nowcasts are expected to be more reliable than forecasts, the ability to provide nowcasts was given greater importance by the group than forecasting. It was recognized that missions not only depend on warnings, forecasts, and nowcasts of space weather events, but they need "all-clears" so that they know when they can resume normal operations. In some situations, the time it takes for signals of solar events to propagate from the Sun to Earth and then to the vehicle, including the time for processing signals at Earth, will take far more time than is desirable for the protection of instruments and astronauts on the vehicle. Therefore, crews will want to have autonomous crew situational awareness for vehicle operations. It has been pointed out by Kunches et al. (1991) that astronauts are a "proactive group" with a "spirit of adventure and a desire to chart their own destiny." It would therefore be advantageous to provide the crew with tools to monitor space weather from their vantage point, not only to give them the ability to rapidly respond, but for their own psychological well-being and to maintain a long-term record of actual mission radiation conditions.

Generally, the engineering approach is to harden systems against worst cases; however, the unexpected can always occur. In such circumstances, a number of actions can be taken in response to predictions of poor space weather. Sensors can be safed, noncritical systems can be shut down to prevent damage and latch-up, sensors can be oriented in a direction that is least susceptible to damage, increased attention can be given to monitoring operations and to the interpretation of sensor data, and mission activities can be limited during high-background events.

References

Barbieri, L.P., and R.E. Mahmot. 2004. October–November 2003's space weather and operations lessons learned. *Space Weather* 2: S09002, doi:10.1029/2004SW000064.

Kunches, J.M., G.R. Heckman, E. Hildner, and S.T. Seuss. 1991. *Solar Radiation Forecasting and Research to Support the Space Exploration Initiative*. Space Environment Laboratory (SEL) Special Report. National Oceanic and Atmospheric Administration SEL, Boulder, Colo. February.

B

Statement of Task

An ad hoc committee of the Space Studies Board will sponsor a cross-disciplinary workshop on the radiation environments in the inner solar system (1-1.5 AU) and their effects on astronauts and operational systems in space. The workshop will consist of overview talks and group discussions in the following areas:

- Characterization of the heliospheric radiation environment as understood to date, including required data sources;
- Physical mechanisms of energetic particle acceleration and transport in the heliosphere as understood to date;
- Radiation health hazards to astronauts;
- Radiation effects on materials and spacecraft systems; and
- Mitigation techniques and strategies, including forecasting and operational schemes.

The workshop will bring together experts from a variety of disciplines to identify open questions that will determine the direction of future research on the above topics. Participants will consider in particular the extent that questions in the areas above can be answered by the focused application of current understanding in the relevant physical, biological, and technological fields, and the extent to which basic research will be required to provide the requisite answers. The workshop will concentrate not only on application of current knowledge, but on the basic research into fundamental physical processes that will be necessary for mitigation of the hazards posed by the radiation environment in which manned expeditions to the Moon and Mars will take place. Given the interdisciplinary nature of the workshop, care will be taken to ensure that the highly specialized topics are presented on a level that will be understandable and useful to the members of the various research communities represented at the workshop.

A report of the workshop will be prepared by this organizing committee.

C

Workshop Participants and Agenda

PARTICIPANTS

James Adams	NASA
Gale Allen	NASA
Spiro Antiochos	Naval Research Laboratory
Daniel Baker	Laboratory for Atmospheric and Space Physics
Nasser Barghouty	NASA Marshall Space Flight Center
Timothy Bastian	National Radio Astronomy Observatory
Eric Benton	Oklahoma State University
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David Cooke	NASA
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Stanley Curtis	University of Washington
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Lamont Di Biasi	Southwest Research Institute

Mausumi Dikpati	University Corporation for Atmospheric Research
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George Fisher	University of California, Berkeley, Space Sciences Laboratory
Richard Fisher	NASA Headquarters
Lennard Fisk	University of Michigan
Bernhard Fleck	European Space Agency Research and Scientific Support Department
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Ghee Fry	Exploration Physics International, Inc.
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Dale Gary	New Jersey Institute of Technology
Joe Giacalone	University of Arizona
Barbara Giles	NASA Headquarters
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Timothy Guild	Boston University
Herbert Gursky	Naval Research Laboratory
Dennis Haggerty	Johns Hopkins University Applied Physics Laboratory
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Insoo Jun	Jet Propulsion Laboratory
Justin Kasper	Massachusetts Institute of Technology
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William Kosmann	Orbital Sciences Corporation
Jonathan Krall	Naval Research Laboratory
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Merav Opher	George Mason University, Department of Physics and Astronomy
Alexei Pevtsov	National Solar Observatory
Lawrence Pinsky	University of Houston
Simon Plunkett	Naval Research Laboratory
John Raymond	Smithsonian Astrophysical Observatory
Geoffrey D. Reeves	Los Alamos National Laboratory
Edmond Roelof	Johns Hopkins University Applied Physics Laboratory
Peter Roming	Pennsylvania State University
Ilia Roussev	University of Michigan
Jennifer Rumberg	NASA
Robert Rutledge	NASA Johnson Space Center
Walter Schimmerling	NASA Bioastronautics Research Division (retired)
Nathan Schwadron	Boston University
Christopher Scolese	NASA
Richard B. Setlow	Brookhaven National Laboratory
Peggy Ann Shea	Air Force Research Laboratory (emeritus), Center for Space Plasma and Aeronomic Research, University of Alabama, Huntsville
Howard Singer	National Oceanic and Atmospheric Administration Space Environment Center
Edward Sittler	Goddard Space Flight Center
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Dennis Socker	Naval Research Laboratory
Harlan Spence	Boston University Center for Space Physics
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Adam Szabo	NASA Goddard Space Flight Center
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Ronald Turner	ANSER Corporation
Tycho von Rosenvinge	NASA Goddard Space Flight Center
William Wagner	NASA
Michael Wargo	NASA Headquarters
John Watts	NASA Marshall Space Flight Center
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Mark E. Wiedenbeck	Jet Propulsion Laboratory
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Gary Zank	Institute of Geophysics and Planetary Physics
Neal Zapp	NASA Johnson Space Center, Space Radiation Analysis Group
Jie Zhang	George Mason University
Thomas Zurbuchen	University of Michigan Department of Atmospheric, Oceanic, and Space Sciences
Ronald Zwickl	NOAA/Space Environment Center

AGENDA

Sunday, October 16, 2005

6:00 p.m.-8:00 p.m. Welcoming Reception

Monday, October 17, 2005

8:30 a.m.	SESSION ONE	Chaired by Gordon Emslie
	NASA's Vision for Space Exploration	Christopher Scolese
	What Are the Forms of Hazardous Radiation?	Stanley Curtis
	End-to-End Overview of Hazardous Radiation Aspects	Lennard Fisk
10:50 a.m.	SESSION TWO	Chaired by Joe Giacalone
	Solar Energetic Events—An Overview	Christina Cohen
	Role of Sun-Solar System Connections	Richard Fisher
	Impact on the Lunar Program	Michael Wargo
12:00 p.m.	LUNCH	
1:15 p.m.	SESSION THREE	Chaired by Ronald Moore
	Radiation Exposure in Giant Events/ Transport Code Development	Lawrence Townsend
	Forecasting	Ronald Zwickl
	CME/Flare Mechanisms	Spiro Antiochos
	SEP Shock Acceleration	Joe Giacalone
	Propagation of SEP Drivers	Ilia Roussev
4:00 p.m.	DISCUSSION GROUP SESSION 1	
6:00-7:00 p.m.	POSTERS	

Tuesday, October 18, 2005

8:30 a.m.	SESSION FOUR	Chaired by Bernhard Fleck
	Collaborative Efforts: Agency-wide Radiation Challenges	Gale Allen
	Galactic Cosmic Ray Composition, Spectra, and Time Variations	Mark Wiedenbeck
	Long-Term Trends in the Intensity of Cosmic Rays and Solar Events	Frank McDonald
10:20 a.m.	SESSION FIVE	Chaired by Robert Lin
	Radiation Belt	Geoffrey Reeves
	Ionospheric and Magnetospheric Plasma Effects	David Cooke
	Radiation on Planetary Surfaces	Martha Clowdsley
12:20 p.m.	LUNCH	
1:45 p.m.	SESSION SIX	Chaired by Stephen McKeever
	Operational Aspects of Space Radiation	Mark Weyland
	Understanding and Mitigating the Radiation Hazards of Space Travel: Progress and Future Needs	Richard Setlow
	Challenges for Electronics in the Vision for Space Exploration	Kenneth LaBel
	Risk Management Strategies During Solar Particle Events on Human Missions to the Moon and Mars	Ronald Turner
4:00 p.m.	DISCUSSION GROUP SESSION 2	
6:00-7:00 p.m.	POSTERS	

Wednesday, October 19, 2005

8:30 a.m.	DISCUSSION GROUP SESSION 3
10:45 a.m.	DISCUSSION GROUP SESSION 4
12:15 p.m.	LUNCH
1:45 p.m.	DISCUSSION GROUP SESSION 5
4:00 p.m.	DISCUSSION GROUP SESSION 6
6:30 p.m.	RECEPTION/BANQUET

Thursday, October 20, 2005

8:30 a.m.	WORKING GROUP PRESENTATIONS AND GENERAL DISCUSSION
12:00 p.m.	ADJOURN

D

Biographies of Committee Members and Staff

DANIEL N. BAKER, *Chair*, is a professor at the University of Colorado and the director for the university's Laboratory for Atmospheric and Space Physics. Dr. Baker's primary research interests are in plasma physical and energetic particle phenomena in the planetary magnetospheres and in Earth's magnetosphere. He also conducts space instrument design, space physics data analysis, and magnetospheric modeling. He has participated in many space science missions, including Pioneer 10 and 11, SAMPEX, POLAR, CLUSTER, and IMEX. He is also active in the teaching of space physics and public policy, as well as outreach to the space technology community and the general public. Prior to his appointment at the University of Colorado in 1993, Dr. Baker was director of NASA's Laboratory for Extraterrestrial Physics at the Goddard Space Flight Center. Earlier, he was leader of the Space Plasma Physics Group at the Los Alamos National Laboratory. He has been the U.S. representative to the International Scientific Committee on Solar-Terrestrial Physics Research and was a member of the NASA Space Science and Applications Advisory Committee. Dr. Baker was a member of the National Research Council's (NRC's) Solar and Space Physics Survey Committee (2001-2003) and the Panel on Atmospheric-Ionospheric-Magnetospheric Interactions (2001-2003). Currently the chair of the NRC Committee on Solar and Space Physics, he has served on the Space Studies Board (1996-1999) and the Steering Committee for the Workshop on Reducing Space Science Research Mission Costs (1996-1997; 2004-2007) and the Committee on the Scientific Context for Space Exploration (2004-2005). He is also a past member of the Panel on Long-Term Observations (1985-1988) and the Committee on Solar and Space Physics (1984-1986).

LESLIE A. BRABY is research professor of nuclear engineering at Texas A&M University's Department of Nuclear Engineering. His research focuses on radiation dosimetry, microdosimetry, biological effects of radiation, and food irradiation. Dr. Braby serves on the National Council on Radiation Protection and Measurement. He previously served as a staff scientist and acting manager in the Biology and Chemistry Department of the Pacific Northwest National Laboratory.

STANLEY CURTIS, recently retired from the Fred Hutchinson Cancer Research Center, is an affiliate professor in the Department of Health and Occupational Safety at the University of Washington. Dr. Curtis received his Ph.D. in physics from the University of Washington in experimental cosmic ray physics. He has devoted his career to studying the effects of radiation on living cells, first from the viewpoint of killing cancer cells and more recently from the viewpoint of radiation-induced malignant transformation. He has long been interested in mathematically modeling radiation-induced effects in humans and in improving risk estimates at low doses and dose rates from both high and low linear energy transfer radiation. Dr. Curtis has served on national and international committees involved in determining radiation risk in space. He served on an NRC panel in the early 1970s, the Radiobiological Advisory Panel to the Committee on Space Biology and Medicine, Space Science Board, (1971-1973). He has also served on the Committee on High Energy and Space Radiation (1974-1978) and was a member of the National Council on Radiation Protection and Measurements (NCRP) from 1987 to 1993, as well as three NCRP committees studying radiation risk in space. He was also the chair of the Committee on Space Research of the International Council for Science Subcommittee on Radiation Environment, Biology and Health (1996-2000). He is the author of more than one hundred papers on the subject of radiation effects on cells and radiation risk estimation.

JACK R. JOKIPII is Regents' Professor within the Lunar and Planetary Laboratory at the University of Arizona. Dr. Jokipii's research in the areas of theoretical astrophysics and space physics is primarily related to the transport and acceleration of cosmic rays and energetic particles in the solar wind and in the Galaxy with major current thrusts centering on work on the Voyager, Ulysses, and the Advanced Composition Explorer (ACE) space missions. Dr. Jokipii and his research group have been guest investigators on these missions and specialize in theoretical interpretation and modeling of the observations. Specifically, Dr. Jokipii's group is currently in the midst of an extensive program of theoretical research to determine the transport coefficients of energetic particles in irregular (turbulent) plasmas and magnetic fields, avoiding the approximations used previously. He is a member of the National Academy of Sciences. His NRC service includes his membership from 2001 to 2003 on the Solar and Space Physics Survey's Panel on Theory, Computation, and Data Exploration. He serves on the NRC Committee on Solar and Space Physics, and was a member of the Panel on Space Sciences and is current chair of the Panel on Physical Sciences of the NRC Policy and Global Affairs Division's Associateship Program.

WILLIAM S. LEWIS is principal scientist with the Space Research and Engineering Division of the Southwest Research Institute. His primary research interest is in the area of auroral physics. He has co-authored papers on Jupiter's x-ray and far-ultraviolet aurora, Earth's proton aurora, Europa's sputter-produced atmosphere, and the Cassini Ion and Neutral Mass Spectrometer investigation. He is currently involved in studies using data obtained with the far-ultraviolet imaging system on the Imager for Magnetopause-to-Aurora Global Exploration (IMAGE) spacecraft, with particular emphasis on the proton aurora. He served as a consultant to the science and technology definition teams for NASA's Magnetospheric Multiscale, Geospace Electrodynamic Connections, and Living With a Star/Geospace missions and is at present a consultant to the recently formed Solar Probe definition team. Dr. Lewis has been involved in the preparation of several NRC documents. As consultant to the Solar and Space Physics Survey Committee, he worked with the committee and NRC staff on the preparation of the first decadal survey in solar and space physics, *The Sun to the Earth—and Beyond*. He has also worked closely with the NRC Committee on Solar and Space Physics on *Plasma Physics of the Local Cosmos* and a popular booklet based on the decadal survey report. Dr. Lewis is a member of the American Geophysical Union (AGU) and chaired the Web site committee of the AGU Space Physics and Aeronomy section (July 1998-July 2000). He serves on the NRC Committee on Solar and Space Physics.

JACK MILLER is currently principal investigator and leader of a group at the Lawrence Berkeley National Laboratory conducting and analyzing the results of accelerator experiments with high-energy heavy ions, with an emphasis on the study of heavy-ion fragmentation and transport in matter. These studies are directed primarily toward the assessment and mitigation of risks to humans in space outside the geomagnetosphere. The experiments focus on characterizing the radiation field produced by interactions of the high-energy heavy-ion component of galactic cosmic radiation with spacecraft and planetary habitat shielding materials and biological organisms, including humans. Dr. Miller's professional interests and experience include nuclear physics with heavy ions; sources and effects of space radiation, in particular the heavy ions in the galactic cosmic radiation; simulation of the space radiation environment at particle accelerators; and theoretical modeling of space radiation effects. He received a Ph.D. in physics from the University of California in 1987, an M.S. in physics from San Francisco State University, and a B.S. in physics at the University of Michigan.

WALTER SCHIMMERLING is the former program scientist for NASA's Space Radiation Health Program, Bioastronautics Research Division. Dr. Schimmerling served as a research biophysicist and senior research scientist at the Lawrence Berkeley National Laboratory from 1972 to 1989. He also served as a NASA visiting senior scientist at the Jet Propulsion Laboratory, manager of the Radiation Health Program at NASA Headquarters, and program director of the joint NASA-National Cancer Institute research project on genomic instability. He is the author of numerous publications on mitigating the health effects of radiation during spaceflight. He was also the chief scientist of the Space Life Sciences Division of the Universities Space Research Association.

HOWARD J. SINGER is chief of the Science and Technology Infusion Branch at the National Oceanic and Atmospheric Administration's (NOAA's) Space Environment Center (SEC). In addition, he is the project scientist for the current and future NOAA Space Environment Monitor instruments on the Geostationary Operational Environmental Satellite (GOES) spacecraft and the responsible scientist for the GOES spacecraft magnetometers. Prior to joining SEC, Dr. Singer was with the Air Force Geophysics Laboratory, where he was the principal experimenter for the fluxgate magnetometer on the joint Air Force-NASA Combined Release and Radiation Effects satellite. Dr. Singer's research is in the area of solar-terrestrial interactions, ultra-low-frequency waves, geomagnetic disturbances, storms, and substorms. He has served on various NASA, National Science Foundation (NSF), U.S. Geological Survey, and NRC committees, including recent service on the NASA Living With a Star Geospace Mission Definition Team. From 2001 to 2003 he served on the NRC Solar and Space Physics Survey Panel on Atmosphere-Ionosphere-Magnetosphere Interactions. Dr. Singer is currently on the NSF Geospace Environment Modeling Steering Committee and the Editorial Advisory Board of *Space Weather: The International Journal of Research and Applications*. Dr. Singer was co-editor of the 2001 AGU Geophysical Monograph, *Space Weather*. He has received awards from the Air Force, NASA, and NOAA, including the prestigious Department of Commerce Gold Medal for Leadership. He serves on the NRC Committee on Solar and Space Physics.

LEONARD STRACHAN is an astrophysicist at the Harvard-Smithsonian Center for Astrophysics, where he has been working since 1991. He received his Ph.D. in astronomy from Harvard University. Dr. Strachan is a member of the Ultraviolet Coronagraph Spectrometer (UVCS) team on the Solar and Heliospheric Observatory (SOHO) mission. His research focuses on developing remote sensing techniques and instrumentation for studying the solar corona and solar wind using extreme ultraviolet radiation spectroscopy. Specifically, he is interested in determining the plasma properties and large-scale characteristics of the solar wind acceleration region of the solar corona. Such measurements are important for understanding the processes that drive both steady and dynamic solar wind. His previous experience includes participating in the instrument development and flight operations of the Spartan 201 space shuttle experiment. Dr. Strachan was a member of the NASA Solar and Heliospheric Management and Operations Working Group (2001-2004) and the NASA Sun-Solar System Connection Roadmap Foundation Committee (2004-2005). He serves on the NRC Committee on Solar and Space Physics.

LAWRENCE W. TOWNSEND is a professor in the Department of Nuclear Engineering, University of Tennessee. Between 1970 and 1977 he served in the U.S. Navy as a nuclear submarine engineering officer. From 1981 until 1995 he held positions as research scientist and senior research scientist at NASA Langley Research Center. While at NASA, Dr. Townsend received numerous scientific awards, including NASA's highest research honor—a NASA Exceptional Scientific Achievement Medal for outstanding contributions to the understanding of nuclear interactions of cosmic radiation with matter and its implications for space radiation exposure and shielding. He is a council member of the National Council on Radiation Protection and Measurements. His research interests include space radiation transport code development, space radiation shielding, theoretical modeling of secondary neutron production cross sections and spectra from energetic proton and heavy-ion interactions with thin and thick targets, modeling production of radioactive and stable heavy nuclides from nuclear spallation, and design of neutron sources, including cold sources, for use in radiography, radiotherapy, neutron activation analysis, and materials studies. He is the principal investigator and leader of the multi-institutional, NASA-funded, Space Radiation Transport Code Development Consortium. Dr. Townsend received a Ph.D. in theoretical nuclear physics from the University of Idaho in 1980, an M.S. in physics from the U.S. Naval Postgraduate School in 1970, and a B.S. in physics from the U.S. Naval Academy in 1969.

RONALD E. TURNER is a principal scientist at ANSER Corporation. Dr. Turner has more than 20 years of experience in space systems analysis, space physics, orbital mechanics, remote sensing, and nuclear and particle physics. He also has extensive experience in radiation effects on humans in space. His recent research as participating scientist on the Mars Odyssey mission has included risk management strategies for solar particle events during human missions to the Moon or Mars. He has been an invited participant at NASA workshops looking at space radiation/biology missions, life science mission requirements for several Mars initiatives, and the impact of solar particle events on the design of human missions. Dr. Turner served on the NRC Safe on Mars study in 2002. He is the senior science adviser to the NASA Institute for Advanced Concepts, an independent institute charged with creating a vision of future space opportunities to lead NASA into the 21st century. Dr. Turner received a Ph.D. in physics from Ohio State University in 1984, an M.S. in physics from the University of Florida in 1978, and a B.S. in physics from the University of Florida in 1977. He was chair of the Aeronautics and Space Engineering Board's Human Health and Support Systems Panel reviewing the NASA capabilities roadmap, and he has been nominated to serve on the NRC Committee on Space and Solar Physics.

THOMAS H. ZURBUCHEN is an associate professor of space science and engineering in the Department of Atmospheric, Oceanic, and Space Sciences at the University of Michigan, where he led the design, manufacturing, and testing of a low-weight time-of-flight mass spectrometer, the Fast Imaging Plasma Spectrometer, part of the spacecraft MESSENGER payload flying to Mercury. Dr. Zurbuchen's research interests include instruments to measure the composition of plasmas in the heliosphere, new particle detectors technologies suitable for future space missions, theoretical models for all major phenomena in the solar atmosphere and its expansion into the heliosphere as the solar wind, theoretical concepts and models for interstellar heliospheric neutral gas and dust behavior and subsequent ionization to form so-called pickup ion population, and theoretical concepts and experimental exploration methods of interaction between the heliosphere and local interstellar medium. From 2001 to 2003, Dr. Zurbuchen served on the NRC Solar and Space Physics Survey Panel on the Sun and Heliospheric Physics. He is a recipient of a Presidential Early Career for Scientists and Engineers Award. He serves on the NRC Committee on Solar and Space Physics.

Staff

DWAYNE A. DAY, *Study Director*, received his Ph.D. in political science from the George Washington University and has previously worked for the Columbia Accident Investigation Board and the Congressional Budget Office. He has previously been both a Verville Fellow and a Guggenheim Fellow at the Smithsonian National Air and Space Museum. He edited *Eye in the Sky*, a history of the early American satellite reconnaissance program, and wrote *Lightning Rod*, a history of the Air Force chief scientist's office. He is associate editor of the German spaceflight magazine *Raumfahrt Concret*, and has served as a guest editor of the *Journal of the British Interplanetary Society.*

ARTHUR CHARO, *Senior Program Officer*, received his Ph.D. in physics from Duke University in 1981 and was a postdoctoral fellow in chemical physics at Harvard University from 1982 to 1985. Dr. Charo then pursued his interests in national security and arms control at Harvard University's Center for Science and International Affairs, where he was a fellow from 1985 to 1988. From 1988 to 1995, he worked in the International Security and Space Program in the U.S. Congress's Office of Technology Assessment (OTA). Dr. Charo has been a senior program officer at the Space Studies Board (SSB) of the NRC since OTA's closure in 1995. His principal responsibilities at the SSB are to direct the activities of the NRC Committee on Earth Studies and the NRC Committee on Solar and Space Physics. Dr. Charo is a recipient of a MacArthur Foundation Fellowship in International Security (1985-1987) and was the American Institute of Physics's 1988-1989 American Association for the Advancement of Science Congressional Science Fellow. In addition to directing studies that have resulted in some 28 reports from the NRC, he is the author of research papers in the field of molecular spectroscopy; reports to Congress on arms control and space policy; and the monograph *Continental Air Defense: A Neglected Dimension of Strategic Defense* (University Press of America, 1990).

CATHERINE A. GRUBER, *Assistant Editor*, joined the SSB as a senior program assistant in 1995. Ms. Gruber came to the NRC in 1988 as a senior secretary for the Computer Science and Telecommunications Board and has also worked as an outreach assistant for the National Academy of Sciences-Smithsonian Institution's National Science Resources Center. She was a research assistant (chemist) in the National Institute of Mental Health's Laboratory of Cell Biology for 2 years. She has a B.A. in natural science from St. Mary's College of Maryland.

CELESTE NAYLOR, *Senior Program Assistant*, joined the NRC and the SSB in June 2002. She has worked with the Committee on Astronomy and Astrophysics, the Committee on Assessment of Options to Extend the Life of the Hubble Space Telescope, and also with the Committee on Microgravity Research and the Task Group on Research on the International Space Station. Ms. Naylor is a member of the Society of Government Meeting Professionals and has more than 7 years of experience in event management.

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Acronyms

ACE	Advanced Composition Explorer
AFWA	Air Force Weather Agency
ALARA	as low as reasonably achievable
ATST	Advanced Technology Solar Telescope
AU	astronomical unit
CCD	charge coupled device
CCMC	Community Coordinated Modeling Center
CEDAR	Coupling, Energetics, and Dynamics of Atmospheric Regions
CEV	Crew Exploration Vehicle
CISM	Center for Integrated Space Weather Modeling
CME	coronal mass ejection
CPD	crew passive dosimeter
CPDS	charged particle directional spectrometer
CSSP	Committee on Solar and Space Physics
DDREF	dose and dose-rate effectiveness factor
DOD	Department of Defense
ERR	excess relative risk
EUV	extreme ultraviolet
EV1	velocity vector
EV2	zenith direction
EV3	antivelocity vector
EVA	extravehicular activity
EV-CPDS	extra-vehicular charged particle directional spectrometer

FASR	Frequency Agile Solar Radio (telescope array)
GCR	galactic cosmic radiation
GEM	Geospace Environment Modeling
GOES	Geostationary Operational Environmental Satellite
HZE	high Z energetic ion ($Z > 2$)
IMAGE	Imager for Magnetopause-to-Aurora Global Exploration
IMF	interplanetary magnetic field
ISS	International Space Station
IV-CPDS	intra-vehicular charged particle directional spectrometer
JSC	Johnson Space Center
LEO	low Earth orbit
LET	Linear Energy Transfer
LWS	Living With a Star
MARIE	Mars Radiation Environment Experiment
MURI	Multidisciplinary University Research Initiative
NASA	National Aeronautics and Space Administration
NCRP	National Council on Radiation Protection and Measurements
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
RAM	radiation area monitor
RHESSI	Ramati High Energy Solar Spectrographic Imager
SAA	South Atlantic Anomaly
SDO	Solar Dynamics Observatory
SEC	Space Environment Center
SEP	solar energetic particle
SHINE	Solar, Heliospheric, and Interplanetary Environment
SIREST	Space Ionizing Radiation Environments and Shielding Tools
SOHO	Solar and Heliospheric Observatory
SOLPENCO	Solar Particle Engineering Code
SRAG	Space Radiation Analysis Group
SSP	solar and space physics
STEREO	Solar Terrestrial Relations Observatory
TEPC	tissue equivalent proportional counter
TIMED	Thermosphere Ionosphere Mesosphere Energetics and Dynamics (mission)

TLD	thermoluminescent detector
TRACE	Transition Region and Coronal Explorer
USAF	U.S. Air Force
VSE	Vision for Space Exploration