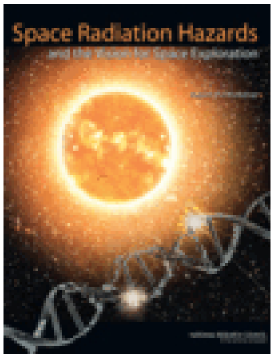
Free Executive Summary



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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Fulfilling the President's Vision for Space Exploration (VSE) will require overcoming many challenges. Among these are the hazards of space radiation to crews traveling to the Moon and Mars. To explore these challenges in some depth and to examine ways to marshal research efforts to address them, NASA, NSF, and the NRC sponsored a workshop bringing together members of the space and planetary science, radiation physics, operations, and exploration engineering communities. The goals of the workshop were to increase understanding of the solar and space physics in the environment of Earth, the Moon, and Mars; to identify compelling relevant research goals; and discuss directions this research should take over the coming decade. This workshop report presents a discussion of radiation risks for the VSE, an assessment of specifying and predicting the space radiation environment, an analysis of operational strategies for space weather support, and a summary and conclusions of the workshop.

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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Townsend, L.W., F.A. Cucinotta, and J.W. Wilson. 1992. Interplanetary crew exposure estimates for galactic cosmic rays. *Radiat. Res.* 129:48-52.

[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.

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.

[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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