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Space Radiation Hazards and the Vision for Space Exploration: A Report on the October 2005 Wintergreen Conference

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Naturally occurring radiation to which astronauts may be exposed come in three main forms: galactcosmic rays (GCRs), charged particles accelerated to high energies by eruptive events at the Sun (solar energetic particles, or SEPs), and highly energetic particles trapped in the inner magnetospheres of the Earth and other magnetized planets.

Figure 1 shows the various types of radiation that pervade our solar system (heliosphere). Humans traveling outside the confines of Earth's atmosphere are subjected to GCRs, SEPs, and trapped magnetospheric particles. All three forms of radiation can present serious health risks to astronauts (Table 1) and can adversely affect the technological systems on which both astronaut safety and mission success depend.

Protecting astronauts from space radiation has been of intense concern to NASA since the beginning of the human space program. In particular, NASA's Vision for Space Exploration (VSE) calls for a human mission to the Moon by 2020 and eventually for expeditions to Mars. The implementation of the VSE program, which will take astronauts beyond the relative safety of low-Earth orbit, has given efforts to understand and manage the space radiation threat a challenging new context and urgency.

To explore the implications of this new context for the solar and space physics community, NASA, the National Science Foundation, and the National Research Council

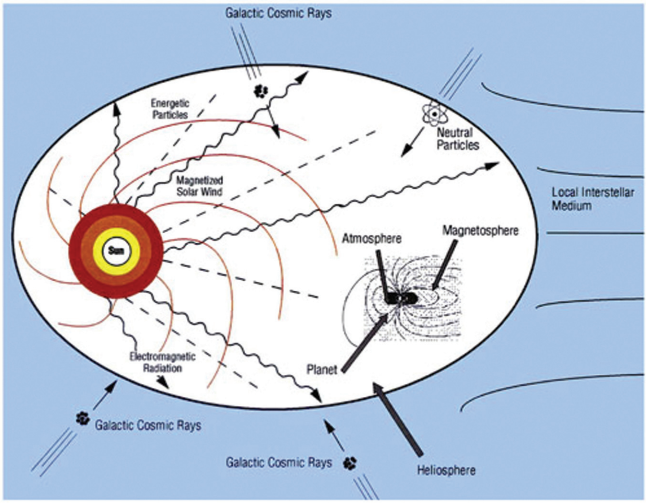

Figure 1. A schematic of the Sun and its region of influence, called the "heliosphere." The heliosphere is embedded within the local interstellar medium (shown in blue). Solar energetic particles, galactic cosmic rays (from outside the heliosphere), and energetic particles within planetary magnetospheres all represent a significant radiation risk to humans traveling in space.

	Effect
Deterministic (acute)	gastrointestinal damage (nausea, vomiting) skin damage (blistering, peeling) hemorrhaging death
Deterministic (late)	Cataracts central nervous system damage
Stochastic	Leukemia solid cancers genetic changes

Table 1. Biological Effects of Exposure to Ionizing Radiation.

sponsored a multidisciplinary conference, "Solar and Space Physics and the Vision for Space Exploration," From 16 to 20 October 2005, approximately 120 members of the space science, planetary science, radiation physics and health, operations, and engineering communities gathered at the Wintergreen Resort, near Charlottesville, Virginia, for tutorial talks and focused discussions covering all aspects of health and operational problems associated with space radiation. Experts from the different disciplines represented at the conference reviewed the present state of knowledge and understanding of the space radiation environment, the effects of radiation on human health and technological systems, and operational capabilities and needs. The participants also met in smaller discussion groups (labeled A through F) to address, in a workshop-like setting, specific key topics (Table 2). The findings of the six discussion groups were presented and discussed in plenary session on the final day of the conference.

A National Research Council report was published in October 2006 based upon the 2005 workshop; this article summarizes the NRC report.

Predicting the Space Radiation Environment

A central theme of the Wintergreen conference was the importance, for mission design, planning, and operations, of developing a reliable capability to predict the space radiation environment, on both short (days to weeks to months) and long (years to decades) timescales. Of greatest interest to mission planners and operators is the ability to predict intense SEP events, such as those that occurred in August 1972 between the Apollo 16 and 17 missions. If timed differently, those events could have caused astronauts caught on the surface of Moon without adequate protection to develop the symptoms of acute radiation sickness [*Parsons and Townsend,* 2000].

The current state of our capability to predict such events and the observational and modeling requirements for improved predictions were the principal focus of the discussions held by discussion groups B and C. The participants identified five quantities that models should be able to predict to be of maximum usefulness for the human exploration program: (1) the onset time for a SEP event, (2) its time-intensity profile, (3) the 'spectral indices' of the energy spectrum, (4) the shock arrival time, and (5) the heterogeneity in the particle velocity distribution (a lower priority). Unfortunately, however, such predictions are beyond the capability of existing models, such as the empirically based climatological models in use by NOAA and the U.S. Air Force, and of observation-based schemes used to predict the onset of solar flares and coronal mass ejections (CMEs).

Group	Topic
A	Prediction on timescales of years to decades and solar cycle variability
B	Solar active regions, flares, and coronal mass ejections
C	Propagation of events in progress
D	Earth, lunar, and planetary (Mars) environments
E	Dosimetry
F	Effects on spacecraft, instruments, and communications

Table 2. Solar and Space Physics and the Vision for Space Exploration Discussion Groups.

Achieving the necessary predictive capability requires the further development and refinement of physics-based research models of CME initiation and of SEP acceleration and transport. Progress in this area requires, in turn, improved understanding of the conditions that lead to the explosive release of energy from the Sun, the mechanisms by which such releases produce energetic particles, and the factors that influence the propagation of energetic particles in the heliosphere. Critical both to advancing our understanding of the underlying physics of CME/flare onset and SEP production and to the development and validation of models are improved observations of the Sun and the inner heliospheric environment. Such data will be provided by missions like NASA's Solar Terrestrial Relations Observatory (STEREO), Solar Dynamics Observatory (SDO), Solar Probe, and Solar Sentinels; JAXA's Solar-B (Hinode); ESA's Solar Orbiter, as well as by advanced ground-based telescopes now planned or under development.

The development of advanced predictive models, the participants agreed, is a long-term goal, one whose realization lies a number of years in the future. In the meantime, 'nowcasting' techniques that predict the total radiation dose and the temporal evolution of the dose after the solar energetic particles begin to arrive have the potential to provide at least a short-term predictive capability until physics-based models are available. Moreover, improved prediction of 'all clear' periods–for example those with a low probability of SEP occurrence–should be achievable in the near-term owing to a better understanding of the signatures indicative of incipient CME or flare eruption.

Long-term (solar cycle, secular) variations in the radiation environment were the topic of a presentation on the historical GCR and SEP event record and of discussions by Group A. Nitrogen oxides (NOy) and Beryllium-10 (10Be) are produced by the interaction of SEPs and GCRs, respectively, with the upper atmosphere. They precipitate out of the atmosphere and are preserved in the layers of polar ice that build up over time, thus forming a record of GCR and SEP fluxes at 1 astronomical unit (1 AU; the distance between the Earth and the Sun) during past epochs. Analysis of 10Be and NOy concentrations in ice core samples shows that with respect both to GCR intensity and to the frequency with which large SEP events occur, the present-day radiation environment at 1 AU appears to be relatively mild compared with past epochs. 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 [*McCracken et al.,* 2001]. The largest of these events appears to have been the 'Carrington' event of 1859, so named because it was the first white-light solar flare identified by English astronomer Richard Carrington.

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 [*Townsend et al.,* 2005]. Similarly, the ice core record, interpreted in the light of historical auroral and sunspot observations, indicates that GCR fluxes, which are modulated by the heliospheric magnetic field, were greater during past epochs than at present because of lower levels of solar activity in the past (for example, during the Maunder Minimum, 1645–1715) [*McCracken et al.,* 2004]. Conference participants stressed the importance of continued research to establish the limits of long-term variability in the space radiation environment.

Because GCR intensity and SEP event occurrence are ultimately controlled by the level of solar activity, the ability to predict the amplitude of future solar cycles can help in forecasting the space radiation environment years and decades in advance of a human mission and would be an invaluable asset for long-range mission design and planning. Prediction of a significantly lower level of solar activity at the time of the first human Mars mission, for example, would mean that mission planners would have to take into account much higher GCR fluxes than are observed at present.

While secular changes in solar activity, such as the low level of sunspots that occurred during the Maunder Minimum, may well be impossible to predict, Group A participants examined a number of prediction schemes currently in use or under development and concluded that methods to forecast variations in the level of solar activity on timescales of one or two solar cycles are well within the realm of possibility. Although somewhat controversial, dynamo-based solar magnetic flux-transport models, which incorporate meridional flows and magnetic diffusion, appear to be particularly promising in this regard and may be able to predict solar cycle amplitude 20 to 25 years in the future.

Lunar and Martian Radiation Environments

In addition to GCRs and SEPs, astronauts on future Moon and Mars missions will be exposed to radiation–mostly neutrons–produced by the interaction of the impinging GCRs and SEPs with the lunar and Martian regolith and, in the case of Mars, with the planetary atmosphere. The surface radiation environment on these bodies was the subject of extensive discussions by the members of Group D, with particular attention to Mars.

The radiation environment at Mars's surface is determined by a number of factors, including the chemical composition of the regolith, the composition and depth of the atmosphere, and the energy spectra of the incident charged particles. Model results presented at the conference indicate that given our current knowledge of these factors, existing radiation transport codes [*Wilson et al.,* 1995] can be used to calculate particle fluxes at the must be validated, initially by measurements made in Earth's stratosphere by balloon-borne detectors and ultimately by in situ measurements on Mars.

From Research to Operations

Operational issues related to managing the radiation risks for human lunar and Mars missions were also discussed at the Wintergreen conference, in both plenary sessions and splinter groups. A recurring theme was the importance of the efficient transfer of knowledge–in the form of improved models, data sets, observational capabilities–from the research community to the operations community.

It was noted, however, that such knowledge transfer is nontrivial. For example, while present operational models are too simplistic, improved physics-based research models may be too complex for operational use. The challenge to researchers is to develop models that are not so complex as to be difficult to transition to operational use but that incorporate enough of the relevant physics to make reliable forecasts. Model validation and verification are critical parts of the transition process, which also includes such activities as robust code development, display design, and operator training.

In addition to models, observations of the space environment are an important component of an operational risk mitigation architecture. Such observations can be provided by both operational and research spacecraft and will consist of remote-sensing observations of the Sun and corona and in situ measurements of SEPs, the solar wind, and the heliospheric magnetic field. For example, meeting participants noted the importance of an L1 monitor–a spacecraft positioned between the Earth and the Sun such that its orbit about the Sun is stable–and the absence of funding in NASA's long-range plans for follow-on L1 missions. Figure 2 illustrates the critical role that both models and observations of the space environment play in the flow of information on which operational decisions will be made.

Successfully managing the risks of space radiation requires that meaningful exposure limits be defined based on knowledge of the effects of different kinds and different doses of radiation. Conference participants from the radiation health community reminded the other participants that significant uncertainties exist in this area–for example, with respect to the biological effectiveness of high-charge-and-energy (HZE) particles and neutrons. Reducing radiobiological uncertainties is the dominant focus of NASA's space radiation program and has important implications for both astronaut safety and mission cost.

The preceding highlights some of the key themes from the Wintergreen conference as conveyed in the recently published conference report [*National Research Council,* 2006]. Copies of many of the presentations made during both the plenary sessions and in the discussion groups, along with the program for the conference, can be found on the SSPVSE Web site (http://hesperia.gsfc.nasa.gov/sspvse/). The conference report was prepared by an ad hoc committee working under the oversight of the Committee on Solar and Space Physics of the NRC's Space Studies Board.

In addition to the publications cited in this article, the reader may wish to consult past Space Weather articles on the subject of space radiation and human exploration [e.g., *Foullon et al.*, 2005; *Lanzerotti,* 2005; *Parker,* 2005].

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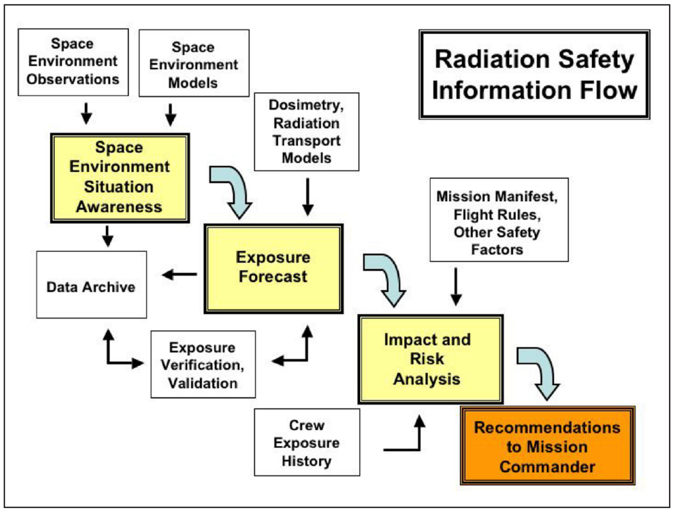

Figure 2. The generic elements of a radiation risk mitigation strategy include space environment situational awareness, radiation exposure forecasting, and exposure impact and risk analysis. These elements combine to generate recommendations to the mission commander, who has the responsibility for keeping the radiation exposure as low as reasonably achievable.

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