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Interplanetary Space Weather and Its Planetary Connection

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Interplanetary travel is not just a science fiction scenario anymore, but a goal as realistic as when our ancestors started to cross the oceans. With curiosity driving humans to visit other planets in our solar system, the understanding of interplanetary space weather is a vital subject today, particularly because the physical conditions faced during a space vehicle's transit to its targeted solar system object are crucial to a mission's success and vital to the health and safety of spacecraft crew, especially when scheduling planned extravehicular activities.

One of the desires of space exploration is to establish a first Mars colony within the next decades. For this type of scenario it is now timely to address relevant space weather issues. Yet whether it is Mars or a different planet, the fundamental facts are that once the target is reached, the local space weather conditions will be a function of the planet's location in the solar system and whether it has a magnetosphere and/or atmosphere around it. Thus, the nature of interplanetary space and planetary atmospheres must be well understood.

During the weeklong European Planetary Science Congress (Berlin, 18–22 September 2006), sessions offered a broad range of science topics related to planetary science and planetary missions. This venue was an ideal environment for a session covering the topic of interplanetary space weather. Recognizing this, a workshop session entitled "Space Weather and Its Planetary Connection" focused on the implications of heliospheric energetic particle environments on technical and biological systems during interplanetary missions and discussed strategies to help prevent short- and long-term radiation effects.

The session consisted of two solicited talks, the first concerning solar energetic particles and the second concerning radiation risks to space travelers. Three contributing talks covered satellite anomalies and launch failures, galactic cosmic ray characteristics, and the ionosphere of Mars. Following the oral presentations, the session continued with 2 hours of dynamic discussions regarding the scientific, technical, and biological issues surrounding interplanetary travel.
In this report, the main results from the talks are summarized and conclusions from the discussions are given.

The Perils of Interplanetary Travel

Routine human missions to the Moon will doubtlessly be the predecessor for any further human interplanetary mission, especially one to Mars. Only several days away from us in space, the Moon offers new opportunities for studying the space environment outside the terrestrial magnetosphere, as well as being a possible host for the first space colony in our solar system.

Apart from the problems caused to spacecraft by the ultrahigh vacuum and extremes of heat and cold in space, spacecraft also have to survive very hostile environments that can severely limit space missions as well as pose threats to humans. This includes phenomena such as ultraviolet, X-ray, and gamma ray radiation, energetic charged particles (ranging from kiloelectron volts to teraelectron volts), plasmas (both high- and low-energy), and "neutrals" (space debris and meteoroids). Table 1 is an overview of the energy, temporal, and first-order spatial range of major radiation environments in the heliosphere, revealing the diversity of their characteristics, as well as illustrating that physical models for their prediction are very different. In the case of a solar energetic particle (SEP) event, charged particles can propagate to remote sites (e.g., a space ship, a planet's environment) if they are magnetically connected to the source region of particle acceleration.

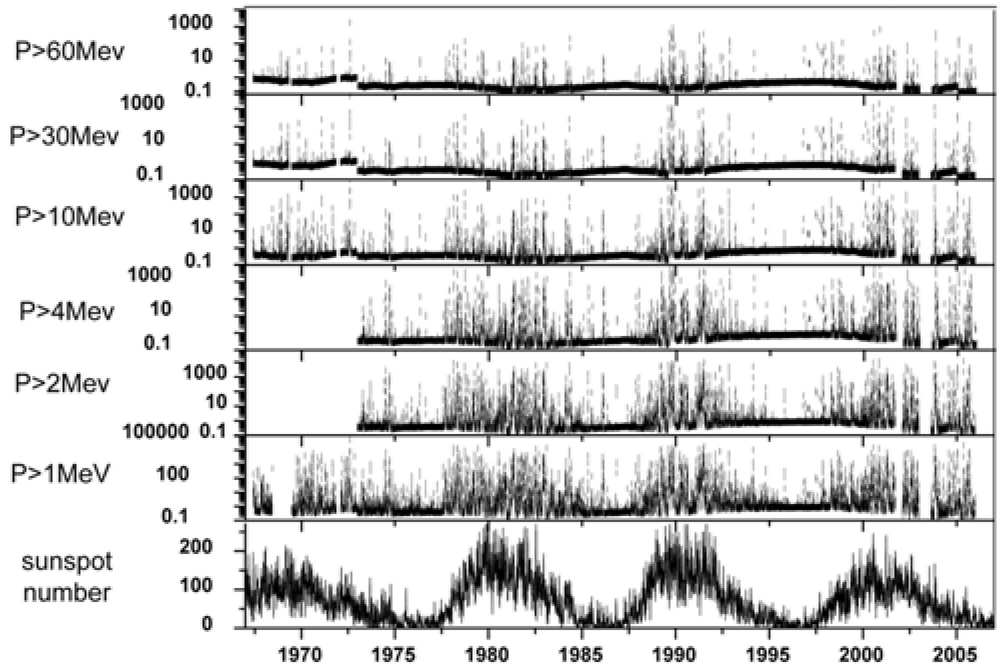
Table 1. Major Radiation Environments in the Heliosphere

Particle Populations	Energy Range	Temporal Range	Spatial Range (First Order)
Galactic cosmic rays	0.1–1000 GeV (the 100- to 1000-MeV fluxes constitute the largest contribution)	continuous (factor 10 variation with solar cycle)	entire heliosphere
Anomalous cosmic rays	<100 MeV	continuous	entire heliosphere
Solar energetic particles	keV–GeV	sporadic (minutes to days)	source region properties (flare/coronal mass ejection (CME) sites and evolution) and bound to CME-driven shock
Energetic storm particles	keV to >10 MeV	hours–day	bound to shock
Corotating interaction regions (CIR)	keV–MeV	few days (recurrent)	bound to CIR shock and compression region
Particles accelerated at planetary bow shocks	keV–MeV	continuous	bound to bow shock
Trapped particle populations	tens of keV to a couple of hundreds of MeV (for protons); tens of keV to several MeV (for electrons)	variations "minutes–years"	variations "height–width"

There was a general consensus throughout the workshop that the populations of energetic particles in various regions of the heliosphere, as well as transient solar particle events and cosmic rays, are the primary radiation hazards for current space missions and future interplanetary travel. The different radiation environments (for example, near Jupiter, on Mars, or even near the heliopause) originate from different sources of particle populations, such as galactic and anomalous cosmic rays or solar energetic particles, accelerated through different physical processes in the heliosphere and interstellar medium.

The particle populations listed in Table 1 are all a function of solar activity, though each in their own way. For example, it is well known that the galactic cosmic ray (GCR) flux in the solar system is modulated by solar activity. During solar maximum (when sunspot number is at its highest) the increase in the interplanetary magnetic field strength, as well as its polarity and the level of solar wind turbulence, enhances shielding of the heliosphere against penetrating GCR particles. Therefore the GCR population is most intense during solar minimum. On the other hand, particles constituting a SEP event can be linked to either a solar flare and/or the shock wave driven by a coronal mass ejection (CME). Therefore SEPs are most frequent and intense near solar maximum. At the declining phase of solar maximum, when high-speed solar winds dominate, enhancements in the outer radiation electron belt extending out to geostationary orbit are often observed 1–2 days following an increase in solar wind speed.

Tendencies such as those mentioned here are readily illustrated in profile plots that vary with time. Figure 1 shows how a systematic increase in energetic particle flux is observed at solar maximum when the sunspot number is at its highest. In the course of a solar cycle, the number of CMEs and their average speed increase with rising solar activity (Figure 2).

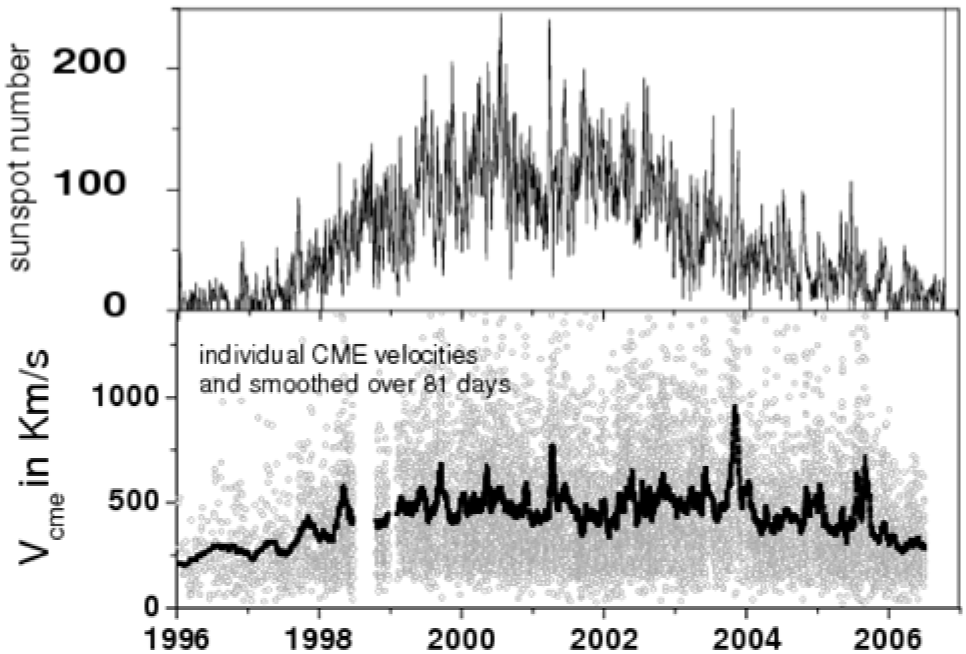


Courtesy of Operating Missions as a Node on the Internet (OMNI) database of the National Space Science Data Center (NSSDC).

Figure 1. (top to bottom) Total proton flux (P) (solar and cosmic origin) above various energy levels and solar activity (daily sunspot number) for four solar cycles.

As evidenced by the number of factors that must be considered to prepare spacecraft for the space hazards, conference attendees agreed that understanding and predicting the perils of interplanetary travel are not simple tasks. Neither is understanding the risks to missions and crew from the local near-target space weather environment once a spacecraft reaches its destination.

For example, planets such as Mars, which lack a substantial internal magnetic field, do not shield space travelers or equipment from energetic particles. For any colony on Mars the mitigation of such particles will be vital for the health of people staying for extended periods of time, although the danger from ordinary "everyday" SEP events is significantly mitigated already by the thin Martian atmosphere. Similar to Earth's ionosphere, short-term ionization increases due to solar radiation (ultraviolet and X-ray) in a planet's atmosphere may cause telecommunications problems.



Courtesy of OMNI database (NSSDC).

Figure 2. (top) Sunspot number as a function of time. (bottom) Coronal mass ejection velocity as a function of time. Individual coronal mass ejections are shown as gray circles, and the 81-day smoothed values are represented by the solid curve.

Workshop participants concluded that applying our understanding and the mitigation of near-Earth space weather phenomena to other target locations in interplanetary space should play a key role in the development of interplanetary space weather mitigation.

Oral Sessions

The workshop's speakers discussed the perils of interplanetary space travel in more detail. The first solicited talk, "Solar Energetic Particles: The Current Status of Their Origin and Space Weather Effects," was presented by Mikhail Panasyuk (Skobeltsyn Institute of Nuclear Physics of Moscow State University, Moscow).

This talk was a review of the current status of the origin of SEPs and their link to space weather. The two well-known SEP empirical models (the JPL-91 model *Feynman et al.,* 1993] and the ESP model [*Xapsos et al.,* 1999, 2000]) are based on the assumption that the 11-year solar activity cycle can be separated into two parts (the 7-year period of the active Sun and the 4-year period of the quiet Sun). Both models use as a basis SEP event distributions over integrated proton fluxes with energies exceeding the given levels. However, the Moscow State University (MSU) model determines the energy spectra and their parameters (average value and standard deviation) rather than particle fluxes of various energies (*Nymmik* [1999]; see also http://elana.sinp.msu.ru/nymmik/models/sep.php). One of the basic assumptions behind the MSU model is that the average rate of SEP events is proportional to solar activity [*Nymmik,* 2007]. The MSU model and the previous two models were compared, and the results were presented as a function of flight duration.

The second invited talk, "Radiation Protection for Manned Interplanetary Missions: Radiation Sources, Risks, Remedies," was presented by Rainer Facius (Division of Radiation Biology, Institute of Aerospace Medicine, German Aerospace Center, Cologne, Germany).

This talk considered how mission designers face the difficult task of containing the overall health risk of astronauts within acceptable limits. Health risks for long-duration interplanetary explorative missions and those encountered so far in manned spaceflight differ significantly in two major features. First, "emergency returns" are ruled out. Second, the risk for acute early radiation diseases (nausea, fatigue, diarrhea, erythema, or even death) becomes non-negligible due to the loss of geomagnetic shielding available in low-Earth orbit (LEO).

The major message that came across during this talk was that radiation risk management striving to conform to predetermined radiation exposure limits&emdash;such as those set by government agencies for LEOs—is likely to be counterproductive since these limits control only the late cancer mortality risk, many years after the mission, rather than the immediate risks faced during the mission.

Instead, a new hazard measure or risk criterion is needed that—in addition to this late radiation risk—allows a unified quantitative treatment of all other nonradiation health and technical risks arising during the mission. In particular, the minimization of the "healthy life span lost" for such a risk criterion appears to be the optimal strategy for mission designers. Presently, countermeasures against radiation risks simply look for the amount of additional shielding matter necessary to reduce mission doses so that the additional mission-related nominal late cancer mortality risk stays below 3%. The consequences that added mass/weight may have for the propulsion system or the exclusion of otherwise useful and safety boosting equipment, or even for the level of secondary radiation outside the shielded volume, are usually not studied, because in LEO missions they are negligible. Further, the major contribution to the healthy life span lost occurs during the mission. The radiation contribution to this loss stems from energetic solar particle events. The probability distribution function for a given mission scenario of acute dose levels due to such events is only poorly predictable. Finally, even if the levels of exposure could be predicted for a given mission scenario without uncertainty, a substantial uncertainty would remain for the prediction of associated health effects since—for both late and early effects—the uncertainties in the dose effect relations are still sizable and the extent to which these dose effect relations might be modified by other factors of the space environment (such as weightlessness) is essentially unknown.

A contributing talk by Natalia Romanova (Institute of the Physics of the Earth, Moscow) was entitled "The Relationship of Satellite Anomalies and Launch Failures to the Space Weather." This talk reported on the possible relationships between satellite anomalies and conditions in the space environment by performing a statistical analysis on anomalies occurring on international and former Soviet Union satellites. For the analysis, various parameters (particle type, particle energy, anomaly type) were considered as a function of solar activity. Preliminary results obtained from a statistical analysis on the origin of launch crashes at Russia's space site (Plesetsk) reveal that in summertime, the crash frequency is 2 times larger compared with other seasons.

Mark Wiedenbeck (Jet Propulsion Laboratory, California Institute of Technology, Pasadena), in a talk entitled "Galactic Cosmic Ray Composition, Spectra, and Time Variations," reviewed the present understanding of the contribution of GCRs to the radiation environment in the inner solar system. Energy spectra of cosmic ray nuclei and the composition of cosmic ray nuclei were shown based on data from various space missions. The heavy ion component is particularly important for space instrumentation and astronaut safety due to its high ionization density. Information about the radial variation of cosmic ray intensity in the heliosphere was given. It was also shown how studies of radioactive isotopes and nitrates preserved in polar ice deposits make it possible to extend the record of cosmic ray incidents on the Earth's surface back hundreds of years. The possibility of a relatively rapid return to higher cosmic ray intensities represents a risk that should be considered in planning manned exploration of the Moon and Mars.

The final contributing talk was presented by Paul Withers (Center for Space Physics, Boston University, Boston, Massachusetts) and was entitled "Space Weather Effects on the Mars Ionosphere due to Solar Flares and Meteors." This presentation concerned the effects of solar flares and meteors on the Mars ionosphere [*Pätzold et al.,* 2005; *Mendillo et al.,* 2006]. Both of these processes increase plasma densities in the bottomside ionosphere at altitudes of about 90 kilometers. Radio waves passing through ionospheric plasma are attenuated if the surrounding neutral atmosphere is sufficiently dense. On Earth, this process is known as *D* region absorption. Thus, solar flares and meteors affect radio wave propagation and can disrupt communications and navigation systems at Mars. The first topside radar sounder at Mars is the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS), aboard ESA's Mars Express spacecraft. MARSIS has experienced problems due to *D* region absorption.

Avoiding Space Weather Hazards

Any trip to the Moon or another planet will mean traversing the Earth's radiation belt in addition to being submitted to continuous GCR radiation and hitherto unpredictable SEP events. The timing of any interplanetary space mission will likely take into account the phase of the solar cycle. Spacecraft shielding requirements, including space storm shelters, on the spacecraft as well as radiation protection facilities on the target (such as the Moon or a planet), need to be taken into consideration with respect to travel time, local target space weather conditions, and the phase of the solar cycle. It is therefore mandatory, especially for a flight to Mars, to implement onboard forecasting capabilities.

The key to understanding radiation protection requires knowledge about the space environment and particle interaction with shielding materials. An important question raised numerous times during the workshop was how the characteristics of the generation of secondary radiation depend on the shielding material Several researchers are developing new forms of shielding materials, and workshop participants agreed that more impetus should be placed on polymer research in regard to the development of low-weight resistant shielding. Of course, as was mentioned in one of the talks, the faster the trip the better; that is, development of innovative transportation technologies and new propulsion systems as well as orbit optimization are highly important if not the most important challenges.

It is a difficult task for scientists to develop physical tools and models that can predict radiation levels in the various domains of space in order to help engineers to design suitable technologies for radiation mitigation for spacecraft and passengers. Solar energetic particle spectra are extremely variable in individual events, and therefore—in a zero-order approach—it is useful to identify a worst-case event as a given threshold that can be used. However, one of the key points discussed was that in order to avoid the obvious (e.g., mass) penalties for spacecraft design that accompany such a worst case, a better risk criterion is needed that allows the joint assessment of all of the many other intercorrelated hazards menacing a healthy mission completion. Session attendees agreed that spacecraft and mission design studies have to compromise between the "healthy life span lost" due to a lack of shielding and the cost and operational burdens of heavy shielding. The biological effect of a radiation dose received over the time period of a week is less dangerous than if the same dose is received instantaneously (e.g., in a few hours). The impact of exposure to galactic heavy ions (which are high-ionizing high-energy particles of high atomic mass) on the chief late radiation effect (cancer mortality 5–30 years after) is still not known with sufficient accuracy.

The ultimate goal is to minimize radiation together with all other health effects and technical hazards by optimizing orbit parameters and shielding. Just prior to this conference, NASA selected a dozen new research proposals focused on better understanding and reducing the risks that space crews of future Moon and Mars missions could face from space radiation. Finally, one should not forget hazard assessment—learning from past failures—as forecasting, mitigation, and hazard assessment go hand in hand.

Feasibility to Use and Integrate Existing Systems

Without doubt, for any upcoming manned interplanetary mission, session participants agreed that understanding local near-Earth space weather capabilities will be critical for the next centuries' mission programs.

There are four main parameters describing any Earth-to-target (e.g., Mars) scenario: (1) telecommunications (signal travel time); (2) target's position (e.g., Mars) with respect to Sun and Earth; (3) estimation of SEP event hazards; and (4) target-Earth phasing to minimize travel time.

Particle flux profile predictions are highly compromised when the target is on the opposite side of the Sun with respect to the Earth, a scenario that by default occurs for more than half of the mission's duration. The detection of back-sided CMEs (sites of possible SEP events) when, for example, Mars is on the farside of the Sun will require space-based coronograph observations from observatories such as the International Space Station, from satellites in low-Earth and Lagrange point orbits, or from satellites in orbits such as those used in the Solar Terrestrial Relations Observatory (STEREO) mission. During some phases of the solar cycle, back-sided CME source regions may be located via helioseimological techniques.

While envisioned manned modules for future space missions to Mars are generally equipped with shielded astronaut shelters, adequate warning is necessary for these to be useful. Effective forecasting capabilities are important for short-term objectives such as being able to predict a SEP event before an astronaut exits the protection of a spacecraft or lunar habitat. In a broader sense, however, space weather monitoring is essential for the understanding of the long-term variations observed in the space environment—the "space climate." This type of information is extremely important in the designing of spacecraft—assurance of operational safety. At the end of the discussions, it was emphasized that more exact space weather and space climate definitions need to be defined.

The Need for an Integrated Approach

Protecting astronauts from radiation is a key factor for future human space exploration and during the past years several meetings have been held [e.g., *Baker et al.,* 2007] and studies have been performed [e.g., *Foullon et al.,* 2005] concerning this issue. There are differences between near-Earth space weather and the local space weather on targets elsewhere in our solar system. Knowledge of near-Earth space weather will serve as the fundament for interplanetary and helio-space weather conditions.
To achieve this knowledge, different scientific communities need to interact with each other. Because of the interdisciplinary aspects, it is important that more interaction between the traditional planet and solar-terrestrial physics communities occurs. This is possible through joint sessions at specific meetings. The session "Space Weather and Its Planetary Connection" at the first European Planetary Science Congress was a first step toward this goal.

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Recommended Sources for Further Information

• European Planetary Science Congress 2006
http://meetings.copernicus.org/epsc2006/index.html

• NASA Selects 12 Research Proposals in Radiation Biology
http://www.nasa.gov/home/hqnews/2006/sep/HQ_06313_radiation_biology_prt.htm

• *Space Weather: Physics and Effects,* edited by V. Bothmer and I. Daglis, Springer Praxis Books, 2006

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