THE MARTIAN RADIATION ENVIRONMENT FROM ORBIT AND ON THE SURFACE.

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Introduction: A good knowledge of the Martian radiation environment and its interactions with Mars is needed for many reasons. It is needed to help unfold the results of the Mars-2001 orbiter's gamma-ray spectrometer (GRS) and neutron spectrometers (NS) to determine elemental abundances on the Martian surface. It is needed to interpret the measurements of the Martian Radiation Environment Experiments (MARIE) on both the Mars 2001 orbiter and lander. It is needed to calculate production rates of cosmogenic nuclides that will be measured in samples returned from Mars. It is needed to determine the doses that astronauts would receive in Martian orbit and especially on the surface of Mars.

We discuss the two types of energetic particles in the vicinity of Mars and the nature of their interactions. Solar energetic particles (SEPs) occur very rarely but can have high fluxes that are dangerous in space. However, their energies are low enough that few solar energetic particles reach the surface of Mars. Their interactions can be fairly easily modeled because SEPs create few secondary particles. Galactic cosmic rays (GCRs) have high energies and are the dominant source of energetic particles on the Martian surface, mainly secondary neutrons. Modeling their interactions is complicated because of the range of nuclei in the GCR and their high energies. Work at Los Alamos on GCR interactions will be presented.

Energetic Particles Near Mars: There are two sources of particles near Mars that have enough energy (energies > ~10 MeV/nucleon) to penetrate matter and induced nuclear reaction: solar energetic particles and galactic cosmic rays. These two types of particles have different energies and different modes of interactions [e.g., 1].

Solar Energetic Particles. SEPs and their acceleration mechanism(s) are controlled by the Sun and the interplanetary fields that it generates. They are about 98% protons, have a proton-to-alpha-particle ratio of about 50 [2], and are ~1% heavier nuclei. Few SEPs have energies > 100 MeV/nucleon [2].

Intense solar particle events can have serious radiation effects to equipment and humans in space. Observations of solar energetic particles since 1956 have been used to develop models predicting the probability of solar particle events [e.g., 3].

SEP produce cosmogenic nuclides in the tops of lunar samples [4]. The average SEP fluxes determined from cosmogenic nuclides are not very different from the average flux during the last four solar cycles [4,5]. Measurements of SEP-produced nuclides also indicate that solar particle events larger than those observed during the last 50 years are very rare [5].

*Galactic Cosmic Rays***.** Particles in the GCR are about 87% protons, 12% alpha particles, and 1% heavier nuclei [6]. Most GCR particles have energies of ~0.1-10 GeV/nucleon. The intensity of GCR particles is modulated by the 11-year solar-activity cycle. There are fewer GCR particles at times of high solar activity. The next period of maximum solar activity is expected to occur in 2000-2001, and the fluxes of GCR particles then will be lower than at most other times in the solar cycle.

On average, a GCR particle produces dozens of secondary particles, including many pi mesons and neutrons. In most objects, GCR-produced neutrons are the dominant particle because they are neutral and travel until they are stopped by nuclear interactions or they escape from the object into space. Neutrons are the main source of cosmogenic nuclides in matter [e.g., 1].

Energetic-Particle Interactions with Mars: The details of the interactions of SEPs and GCR particles with Mars need to be well known to fully understand the Martian radiation environment. The interactions of the relatively-low-energy SEPs with matter are fairly simple. The interactions of the high-energy GCR particles are complicated and very hard to model.

Solar Energetic Particles. SEPs interact with matter mainly by ionization-energy losses that slow and stop most particles. A few SEP particles induce nuclear reactions, but, because of their low energies, SEPs produce few secondary particles [7] in interacting with matter. The thickness of the Martian atmosphere, 15 g/cm^2 on average, stops almost all SEPs with only a few inducing nuclear reactions. SEPs should not be observable at the Martian surface. Some SEP-produced neutrons will reach the Martian surface during the peak fluxes of large solar particle events, as is the case for the Earth.

SEPs at Mars will be a serious radiation hazard above the atmosphere for the very large solar particle events that occur on average once or twice a decade [3,4]. Significant shielding (~5 g/cm^2 of matter) will also be needed to protect Martian samples being returned to Earth from SEPs, especially to prevent production of nuclides in the samples.

While SEPs are an important part of the Martian radiation environment, they will not be discussed much more.

*Galactic Cosmic Rays***.** GCR particles have interaction lengths that are shorter than their ranges in matter. Thus most GCR particles interact before they are stopped in matter. Each GCR particle, because of its average energy of several GeV, induces a cascade of secondary particles. Many particles in this cascade have enough energy to produce additional particles, just as in the Earth, the Moon, and meteorites. In the Earth, very few GCR-produced particles reach the Earth's surface because the Earth's atmosphere is very thick (about 1000 g/cm^2).

At Mars with its thin atmosphere, most GCR proton and alpha-particle interactions will be in the Martian surface, similar to GCR interactions with the Moon [1,8] and meteorites [9]. The cascade of particles made by these interactions is complex and hard to model. Work on numerical simulations on GCR interactions in Mars will be presented below, and the implications of this work discussed.

Because high-Z GCR particles, such as C, O, Si, and Fe nuclei, have relatively-short interaction lengths, most of their interactions will be in the Martian atmosphere. Some primary nuclei or secondary fragments will reach the Martian surface, mainly those with lower charges (Z). The location of these interactions and their products are an important part of the Martian radiation environment.

Studies of GCR Interactions with Mars: Some work has been done at Los Alamos on the interactions of GCR protons and alpha particles with Mars. Most have been done with the LAHET Code System (LCS), which is the Los Alamos high-energy transport code LAHET [10] coupled to the Los Alamos code MCNP [11] for neutrons with energies below 20 MeV. LCS codes can handle 3-dimensional geometries. LCS has been well tested with cosmogenic nuclides in meteorites [9] and lunar samples [8]. Using LCS, studies of GCR interactions in Mars include calculation of the production of 14C in the Martian atmosphere [12] and the Martian surface [13], gamma rays made at Mars [14], and radionuclides made in samples in the Martian surface [15].

In these numerical simulations, the calculated rates for reactions in the Martian surface are similar to those in the Moon. In fact, the production of neutrons in the top 35 g/cm^2 of the Martian surface is higher in the case of a 15-g/cm^2 Martian atmosphere than for the same surface without an atmosphere above it [14]. This higher neutron flux at the surface below an atmosphere occurs because the secondary particles made in the atmosphere more than compensate for the removal of some GCR primary particles by the atmosphere. Most of these extra neutrons for the case with an atmosphere have relatively low (<~50 MeV) energies [15]. These calculations show that the flux of GCR particles (mainly neutrons and protons) at the surface of Mars are similar to those at the surface of an object without an atmosphere, such as the Moon.

Implications for Mars 2001 Experiments: There are two sets of experiments on Mars 2001 that measure energetic radiation at Mars and so are affected by the radiation environment at Mars, the GRS/NS on the orbiter and MARIE on both the orbiter and lander. Measurements by one set can be used to compare results from the other set. For example, the fluxes of neutrons and gamma rays from Mars will vary with GCR modulation, which will be directly measured by sensors on MARIE. The high-energy particles observed by MARIE can then compared with GCR/NS data to better map these variations in primary energetic particles.

Doses measured by MARIE should be sensitive to the fluxes of secondary particles, especially neutrons, as well as primary particles. Neutron fluxes measured by the neutron spectrometers will help to determine the neutron contributions to the dose measured by MARIE. The composition of the surface around the Mars 2001, as determined by the GRS/NS, will be needed to better interpret the measurements by MARIE. This particularly applies to doses.

Modeling of the production and transport of gamma rays made in Martian soil and atmosphere is needed to interpret the measurements of the GRS. The effects of different atmospheric thicknesses and surface water contents were investigated in a study done for Mars Observer [14]. Work is needed to extend this work to a range of surface compositions, such as those inferred from analyses by the Alpha Proton X-ray Spectrometer on the Mars Pathfinder. Data from the fast neutron spectrometer on Lunar Prospector show that the intensity of fast neutrons is sensitive to the surface composition [16], consistent with calculations done by LCS [17].

The measurements by the neutron spectrometers (NS) on Mars 2001 will be better than what would have been measured by the neutron mode of the Mars Observer GRS. As shown by the neutron spectrometers on Lunar Prospector, the neutron data should provide a great deal of information about the composition of Mars [16], especially hydrogen-containing materials [18]. These data will be very valuable in interpreting the GRS gamma-ray spectra and the MARIE dose measurements. The same LCS calculations performed for neutrons should be used for gamma-ray production calculations to couple the calculations done for the GRS and NS.

Martian Returned Samples: The modeling done with LCS for Mars 2001 experiments will determine the fluxes of particles that produce cosmogenic nuclides in Martian samples. These fluxes can then be used with existing sets of cross sections to calculate the production rates of these nuclides, such as has been done in some earlier work [13,15]. These production rates are necessary to convert measured concentrations of cosmogenic nuclides into ages and exposure records for the samples recovered from the Martian surface.

Doses to Martian Astronauts: Calculations done by LCS can be used to extend MARIE's results to the 3-dimensional shapes and the compositions of spacecraft and habitats. For example, certain thicknesses or compositions of shielding on the Martian surface could expose astronauts to higher doses than other thicknesses or compositions. Providing sufficient shielding on the habitat or the heavy equipment needed to cover the habitat may substantially increase the mass of a human mission. Thus, accurate assessment of the radiation levels are a necessity.

The LCS codes could be used to calculate the effects of an intense solar particle event to astronauts in a spacecraft or a Martian habitat. If these calculations show that the doses to astronauts by intense solar particle events would be serious, the timing of a human mission to Mars should be done during the about 4-year period around solar minimum when intense fluxes of solar energetic particles are relatively unlikely [3,5]. However, the fluxes of relativistic (MeV) electrons are the highest in space then [19], and such electrons could be a serious radiation hazard.

Good calculated doses are needed to plan the entire mission. If the doses that astronauts could receive in one mission scenario are too high, alternative scenarios will be needed to reduce doses. Options include better shielding or reducing the mission's duration.

One obvious option, heavily favored in previous Mars mission plans but currently not allowed in the design studies at NASA, is to utilize the performance of a nuclear rocket to enable an opposition-class mission of around 400 days round trip. Such a mission would allow 60 to 90 days on the Mars surface instead of the 500 days required by the conjunction-class missions. Thus, the use of a nuclear rocket could actually reduce the dose to the crew. Consequently, accurate determination of the radiation levels on the Mars surface are essential to any future planning.

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