RESULTS FROM THE MARTIAN RADIATION ENVIRONMENT EXPERIMENT MARIE.

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Introduction: One of the three science instruments aboard the 2001 Mars Odyssey spacecraft is the Martian Radiation Environment Experiment, MARIE. MARIE consists of a stack of silicon detectors, augmented by a Cerenkov detector. MARIE is designed to measure a portion of the particle spectrum of the Galactic Cosmic Rays (GCR), as well as the high fluxes of low-energy protons (energies less than about 100 MeV) that are intermittently produced by active regions on the sun in Solar Particle Events (SPE). MARIE is providing the first detailed information about the radiation environment near Mars.

The GCR are atomic nuclei, stripped of their electrons, that are accelerated through the interstellar medium by supernova shockwaves. Nuclei of every naturally-occurring atomic species are present in the GCR, though ions heavier than iron are relatively rare. The flux is dominated by protons (about 87%) and helium (about 11%), with the remaining two percent divided among all “heavy” ion species.

Although the flux of heavy ions in the GCR is small, their contribution to the radiation dose received by astronauts is considerable. The reason for this is that the dose delivered by a particle of a given velocity is proportional to the square of its charge (Z). Thus a neon ion ($Z = 10$) with an energy of 1 GeV/amu gives a dose 100 times greater than that delivered by a proton at 1 GeV/amu. The contributions of the heavy ions to dose equivalent (the legally-defined measure of exposure) are even larger owing to weighting factors that reach a peak of 20 for densely-ionizing particles.

GCR energy spectra for a given species typically have broad peaks, centered at a few hundred MeV/amu, with long tails out to higher energies. Such energetic particles are capable of passing entirely through any plausible amount of shielding that a spacecraft might have. A dose to astronauts from this exotic form of radiation is therefore unavoidable, as has long been realized [1].

Solar Particle Events generally produce large fluxes of protons, occasionally with significant fluxes of heavier ions also present. Typically, the energy spectra of these particles is much “softer” than those of their counterparts in the GCR, and thus they are less penetrating. It is estimated [2] that shielding consisting of approximately 10 g cm^{-2} of aluminum would reduce the dose from even a large SPE to an acceptable level.

Both GCR and SPE radiation are sources of risk to astronauts on long-duration spaceflight, particularly on missions involving extended durations outside the protection afforded by the geomagnetosphere. As the two types of radiation are quite different from one another, so too are the health risks they present. Because GCR heavy ions do not reach the Earth’s surface, terrestrial life has not evolved defenses against the large and complex damage sites in DNA that these particles are known (from radiobiology experiments at particle accelerators) to cause. The heavy-ion doses encountered in space travel are not large enough to cause acute effects, but there is considerable evidence for long-term harmful biological effects from low doses of heavy ions. On the other hand, SPE – dominated by sparsely-ionizing protons, similar in radiation quality to the flux of muons received on Earth’s surface – are potentially dangerous because the doses received in the absence of adequate shielding can be large enough to cause acute illness, even death, on a short time scale.

As a precursor to human exploration of Mars, it is necessary to measure the radiation environment on the surface and to test model predictions of the environment. The surface environment will be similar to that seen in orbit, modified by the thin Martian atmosphere and by the presence of “albedo” neutrons produced in the upper layers of the surface. Although MARIE does not measure conditions on the surface, it does provide the first detailed measurements from Mars orbit; these results can be tested against radiation transport models in order to refine the models and improve their ability to predict the radiation environment on the surface. It is expected that one or more radiation measuring devices will eventually be placed on a Mars lander to provide radiation data directly from the surface, which will be a critical test of the models.

MARIE Operation: The 2001 Mars Odyssey spacecraft was launched in April, 2001, and reached Mars in October 2001. Aerobraking was used to put Odyssey into a circular, polar orbit some 400 km above the Martian surface, and Odyssey’s science instruments were turned on. MARIE began acquiring data in Mars orbit in March 2002 and has operated successfully since.

MARIE’s silicon detectors record the ionization energy loss (dE/dx) of incident particles. For the particle energies measured by MARIE, the energy deposition in silicon are, to a good approximation, proportional to radiation dose in tissue. Thus pulse-height data from MARIE's silicon detectors can be used as a measure of the dose at Mars. Preliminary comparisons with the HZETRN model of the GCR show good agreement during solar quiet times, although more work is needed to adjust the model for some of the limitations of the detector.

An event is triggered by a coincidence of hits in two 1-mm thick detectors, denoted A1 and A2. These detectors define both the energy threshold and viewing angle of the telescope. Data from each detector is digitized in a 12-bit analog-to-digital converter and stored for later download. MARIE's storage is sufficient to hold about 5×10^5 events. In the absence of a SPE, this corresponds to about 10 days' worth of data.

MARIE is oriented so that its central axis points approximately along the anti-velocity vector of the spacecraft. The mass in this "forward" direction (from MARIE's point of view) has been minimized, but there is considerable mass behind MARIE. Nonetheless, some particles are seen to enter from the backward direction. A detailed understanding of the different efficiencies for forward and backward-going particles, as functions of charge and energy of the incident particles, requires a simulation of the detector that includes all the relevant physical processes: dE/dx energy loss, nuclear interactions, and Coulomb multiple scattering. A detailed model is under development based upon the CERN Monte Carlo code FLUKA [3].

MARIE measures particles between helium and neon accurately over the range of energy from about 70 MeV/nucleon to about 500 MeV/nucleon. At higher energies, these particles can be identified by their species, but their energies cannot be determined. Protons are well-measured in the energy range from 30 to about 100 MeV, a range that is a good match to the proton spectra in a typical SPE. Ions heavier than neon are recorded as hits in the detectors, but no useful dE/dx information is recorded.

As of this writing, MARIE has seen ten solar particle events. For this period of operation, Mars and Earth have been on nearly opposite sides of the sun, so that these events provide interesting new data bearing on the radial and longitudinal distributions of particles produced in SPE. Some events have been simultaneously observed both at Earth and Mars, while others have been seen only at Mars (so-called "backside" events, referring to the far side of the sun as seen from Earth). Detailed analysis of these events, in particular extraction of the proton and helium energy spectra, and correlation with observed active regions on the solar surface, is in progress.

Data obtained from other deep-space missions (the Voyagers and Pioneer 10) strongly suggest a fairly mild average radial gradient in the IMF, so that the flux of GCR particles should not differ substantially between Earth and Mars. This supposition can be checked by comparing the spectra obtained by MARIE in the range of particle charges and energies where it is highly efficient to data for the same particles obtained by near-Earth detectors, in particular ACE/CRIS. A sophisticated algorithm to determine the charge and energy of heavy ions detected by MARIE is being developed. The algorithm makes the fullest possible use of the data recorded by MARIE's multiple dE/dx measurements.

In summary, MARIE has been operating successfully for nearly a year. Solar particle events of considerable interest have been observed, and data have been obtained that will yield GCR spectra from a novel observation point in the solar system.

References:

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