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MODELS FOR GALACTIC COSMIC RAY AND SOLAR ENERGETIC PARTICLES AND THEIR APPLICATION TO SPACECRAFT DESIGN

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Abstract

The effects of radiation environment in interplanetary space must be taken into account for spacecraft design. This is done by modeling this environment and propagating it to the electronic parts of interest within the spacecraft then calculating the effects of this radiation on these parts. This talk will present a survey of the existing models for the interplanetary radiation environment and the results of comparing them with measurements. It will also include a survey of radiation transport methods and methods for estimating the effects of this radiation on spacecraft.

1.0 Introduction

The dominant components of the ionizing radiation environment in interplanetary space that affect the electronic components of spacecraft are galactic cosmic rays (GCRs) and solar energetic particles (SPEs). With the exception of solar cells, electronic components are typically protected by at least 100 mils (0.7 g/cm^2) of aluminum. Solar cells may be protected by cover glass as thin as 2 mils (0.1 g/cm^2). The particle energy required to penetrate into the electronic component sets a lower limit for the energy spectrum of interest for each particle species.

The effects of ionizing radiation on electronic components determine the elemental species that are important to model. Protons make the dominant contributions to total dose. SPE events are the dominant cause of displacement damage in solar cells. Particles with just enough energy to penetrate into the cells are the most effective, as Sharps et al. (2000) have shown. For a typical solar cell cover glass thickness (e.g. 6 mils) electrons with 0.2 MeV just penetrate into the cells while protons must have 4.2 MeV to penetrate. The flux of penetrating solar energetic electrons exceeds that of protons by a factor of ~500 in, for example, the large SPEs of October-November 2003 (Mewaldt et al, 2005). However as Sharp et al. (2000) have shown the effectiveness of stopping protons to create displacement damage is ~500 times greater than electrons, so both SPE protons and electrons complete as the dominant cause of radiation damage to solar cells.

Usually the dominant radiation effects on electronic circuit components are single event effects (SEEs). These are caused by intensely ionizing particles so heavy ions are often sufficiently ionizing to SEEs directly. Protons can also cause SEEs, but typically this occurs only when the proton interacts with a nucleus in the electronic component to create intensely ionizing fragments. Since such interactions are improbable (1 chance in >10^4 protons) heavy ions are usually the dominant cause of SEEs in the GCR environment. When the space radiation environment is dominated by an SPE, protons can become the dominant cause of SEEs for two reasons. First, protons are ~5 times more abundant in SPEs compared to GCRs and second, the SPE elemental fluxes fall rapidly with increasing energy (see for example, Mewaldt et al., 2005). Protons and heavy ions at the same energy per nucleon have ranges that depend on atomic number as A/Z^2, where A is the atomic mass and Z is the atomic number. So the range of a heavy ion at the same energy per nucleon is shorter than that of a proton by a factor of ~2/Z. Since the typical particle passes through hundreds of mils of shielding to reach an electronic component, the initial energy of a heavy ion reaching the component must be significantly higher. Because of the steeply falling elemental spectra in SPEs the flux of protons able to penetrate to the component is even higher. It is the combination of these factors that often overcomes the disadvantage the proton has because it must cause a nuclear reaction to create the intensely ionizing particles needed to cause an SEE.

2.0 Models of Galactic Cosmic Ray Elemental Spectra:

These models must describe the GCR elemental spectra of protons and heavy ions with energies that will penetrate ~100 mils of aluminum (and it is better to extend this down to 25 mils to cover all cases). That corresponds to 10 MeV for protons and higher energies for heavier ions. The model must include the elemental spectra up to at least Fe but should extend to U for complete coverage. There are several existing models that can be used individually or in combination to meet these requirements.

2.1 The Nymmik Model: This model was originally developed by Riho Nymmik back in the early1990s and was adopted as the ISO standard model for the GCR environment. It is the model used in CREME96. The latest update of this model is INTERNATIONAL STANDARD ISO/DIS 15390 that was proposed to the ISO in 2002 and adopted in 2003. It provides the spectra of electrons and all ions from protons to uranium for all energies >10 MeV/nuc. It models the GCR fluxes assuming that they are time invariant beyond the heliosphere. The temporal variation in the fluxes attributed to large scale variations in the heliospheric magnetic field. This results in roughly cyclic variations in the GCR spectra with periods of ~11 and ~22 years. The actual modulation of the interstellar GCR spectra is indexed using the Wolf number (this is a count of the number of spots on the sun following an internationally agreed procedure). The Wolf number serves as a measure of solar activity and is known to be anti-correlated with the GCR flux (see Cliver and Ling, 2001). Cosmic ray modulation can thought of as a consequence of the pileup of interplanetary shocks at the heliospheric boundary. The frequency with which the Sun launches these shocks is correlated with solar activity and hence with the Wolf number. Because of the propagation time of these shocks from the sun to the boundary, the Wolf number is a leading indicator of solar modulation levels extending several months into the future.

2.2 The CHIME Model: This model was developed in the early 90's by Chenette et al. (1994). It provides the spectra of all ions from protons to uranium for all energies >10 MeV/nuc. Like the Nymmik model, CHIME assumes time-invariant interstellar spectra that are modulated by large scale variations in the heliosphere. It uses the theoretical model of Gleeson and Axford (1968) for solar modulation which describes the level of modulation by a single parameter, Φ. CHIME chooses the value for Φ using the 70-95 MeV/nuc helium ion flux as measured on the IMP-8 satellite. The measurements of this flux from IMP-8 are no longer widely available since NASA ended mission operations support in 2001. As Chenette et al. point out in their paper, there are many proxies for the solar activity level, the solar neutron monitors have been found to correlate best with the GCR fluxes that are relevant to radiation effects. While NSF has recently discontinued support for 13 monitors operated by the University of Delaware and the University of New Hampshire, 38 remain in operation, worldwide and the data from many of these is available online in real-time.

2.3 The Badhwar-O'Neill Model: This model was developed first in the 1990s. The most recent revision is O'Neill (2006). It provides the spectra of all ions from protons to nickel for all energies >10 MeV/nuc. Modulation is treated in a way similar to CHIME, but the spherically symmetric Fokker-Planck equation is solved using the methods of Fisk (1971) to obtain the modulated spectra. The solar modulation parameter, Φ, can be determined using measurements of the GCR oxygen spectrum between ~70 and ~200 MeV averaged over 10-40 days as measured by the CRIS instrument on the ACE spacecraft. Alternately, the count rate of the neutron monitor in Climax, Colorado, but this monitor is no longer supported.

3.0 Models of Solar Energetic Particle Elemental Spectra:

3.1 Ellison and Ramaty Model: Ellison and Ramaty (1985) proposed the form given below were J is the elemental flux, E is the energy/nucleon and γ is the power law spectral index. The spectral index, E_0 and K are free parameters.

$$dJ/dE = KE^{-\gamma}\exp(-E/E_0)$$

Mewaldt et al. (2005) give several examples of SPE spectra fit by this form.

3.2 Double Power Law: Bland et al. (1993) proposed using two power laws to fit SPE elemental spectra. The functional form of the double power law is given below where the symbols are the same as above except γ_a and γ_b are the power law spectral indices. These indices, E_0 and C are free parameters. Mewaldt et al. (2005) also give examples of SPEs fit by this form.

$$dJ/dE = CE^{-\gamma_a}\exp(-E/E_0)\,\text{for}\ E \le (\gamma_b - \gamma_a)E_0$$
$$dJ/dE = CE^{-\gamma_b}\left\{[(\gamma_b - \gamma_a)E_0]^{(\gamma_b-\gamma_a)}\exp(\gamma_a - \gamma_b)\right\}\ \text{for}\ E \ge (\gamma_a - \gamma_b)E_0$$

3.3 Weibull Distribution: Xapsos et al (2000a) proposed the following form,

$$dJ/dE = J_0 K\gamma E^{\gamma-1}\exp(-KE^{\gamma})$$

where the symbols are as defined above. Xapsos et al. (2000) show several examples of SPE spectra fit by this form. It appears to be more universally successful than other forms.

4.0 Probabilistic Models for Solar Particle Events

Probabilistic models for SPEs are used to predict the mission cumulative dose and the probable worst-case SPE during the mission. The existing models are due to Feynmann et al. (1990; 1993; 1996; 2002) and Xapsos et al. (1996; 1998; 1999a; 1999b; 2000b; 2004 and 2007).

5.0 Radiation Transport Codes

Codes are available in two forms, Boltzmann Equation solvers (see for example Wilson et al., 1991) and Monte Carlo Methods. Examples of the former are HZETRN (Wilson et al., 1991) and UPROP (Letaw, 1989). There are numerous Monte Carlo codes available. The three most widely used are GEANT (Brun et al., 1994), MCNPX (Waters, 2002) and FLUKA (Ferrari et al., 2005). There is a fourth code HETC-HEDS (Townsend et al., 2005) also transports protons and heavy ions.

6.0 Summary

This paper provides a brief introduction to radiation environment models that needed to predict radiation effects on spacecraft electronic systems. It is intended as a supplement to the talk that will be presented at the meeting. The talk will focus on comparing these models with data in order to select ones for use with the next revision of CREME96.

7.0 References

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