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ABSTRACT

This paper will describe the Cosmic Ray Effects on MicroElectronics (CREME) model that is currently in use to estimate single event effect rates in spacecraft.

1.0 INTRODUCTION

The first models of the intensely ionizing particle environment in space were constructed to estimate the biological effects of these particles. When single event upsets (SEU's) and other single event effects were discovered in the 70's, a detailed model of the intensely ionizing particle environment near the earth's orbit was constructed. The focus of all these models has been the computation of linear energy transfer (LET) spectra, because both the biological and the electronic effects of these particles can be computed from LET spectra. LET is defined as the amount of energy transferred, per unit path length, from an energetic particle to the medium through which it is passing. This energy must be deposited along or near the particle's path. This is different from stopping power (or dE/dx) which is defined as the amount of energy lost, per unit path length, by the energetic particle as it passes through the medium. These two are not the same, since the energy lost may exceed the energy transferred and, on the microscopic scale, the energy is never deposited in the medium at the same place as it is lost. Nevertheless, LET is nearly equivalent to stopping power, and stopping power (computed in the straight-ahead, continuous-slowning-down approximation) is usually used to approximate LET.

2.0 HISTORY

Wallmark and Marcus[1], in their 1962 paper on the minimum size of semiconductor devices, were the first to recognize that cosmic rays would interfere with the performance of the miniaturized components that they envisioned for the future. This interference appeared first as SEU's. SEU's are caused by intensely ionizing particles that can produce a burst of charge or a current transient that is large enough to disrupt the logic state of a microelectronic circuit. SEU's were first reported by Binder et al.[2] in 1975. These authors used a scanning electron microscope to simulate the ionization of a stopping Fe nucleus and demonstrate that the anomalies observed in space were indeed due to cosmic rays.

These early papers were ignored by the radiation effects community. It was not until SEU's due to cosmic rays were reported on the NAVSTAR GPS satellite[3] and SEU's due to alpha particles were discovered in the laboratory [4,5] that research into SEU's began.

The importance of such intensely ionizing particles had already been recognized in the radiobiology community[6,7] and a substantial research program on their unique effects was underway in the 60's. As part of this effort, an LET spectrum for galactic cosmic rays was computed by Curtis and Wilkinson[8]. Their spectrum includes the contributions of the elements up through Fe and corresponds to the minimum of the 11 year solar activity cycle (and therefore the maximum of the cosmic ray intensity cycle). Later, Heinrich[9] used the cosmic ray differential energy spectra from Mason[10] to construct differential and integral LET spectra behind various thicknesses of shielding. These LET spectra only included the contributions from the elements carbon through iron. Because the measurements of Mason were made during the maximum solar cycle, these LET spectra describe the space environment at its mildest.

Following the discovery that single event upsets were due principally to cosmic ray heavy ions, the Laboratory for Cosmic Ray Physics at Naval Research Laboratory undertook the project of constructing a comprehensive model of the intensely ionizing particle environment near earth[11] in 1980. This model will be discussed below.

3.0 Galactic Cosmic Rays

The model for the galactic cosmic ray spectra near earth[11] was constructed using all the published data on galactic cosmic rays. It was decided to model the energy spectra of the elements H, He, and Fe. The remaining elemental spectra could then be constructed from these using constant, or energy dependent elemental ratios. The choice of H, He, and Fe for the model spectra was made because: 1) the H spectral form is unique (because of its unique charge to mass ratio); 2) He is, by far, the best measured of the cosmic ray spectra and it has the same form as the heavier primary elements C, O, and Ne; 3) the element Fe is quite abundant and its spectral form differs somewhat from that of He. With only two spectral forms to model all the elemental spectra from He to Ni, it was decided to model the lighter elements with He and the heavier ones with Fe. The best break point was found to be between S and Cl.

All the data on H, He and Fe differential energy spectra were used to define the forms of the spectra at the extremes of solar minimum and solar maximum. It was found that these spectral extremes could be fit to analytic functions. These analytic functions made computation of particle fluxes very fast. The functions are approximate fits to the data as can be seen, in the case of the Fe spectrum, from the solid lines in fig. 1 (taken from [14]). Some details of the fit are in error, such as the turn up in the spectra at low energies and the asymptotic power law fit at high energies. The low energy turn up is not from galactic cosmic rays, but contributed by a quasi-steady interplanetary component.

Following the publication of the data from the HEAO-C experiments (see, for example, [12] and [13]), the model for cosmic rays was updated to include these and other recent results [14]. The updated model fits the HEAO-C data on the elemental spectra above 900 MeV/amu to $\pm 15\%$ for the elements Li to Ni. The data from the HEAO-C-3 experiment[13] allowed the model to be extended to uranium, by using the Fe spectrum as a model for the spectra of all the heavier elements. With this extension, we have a model for all the cosmic ray elemental spectra at solar maximum and solar minimum.

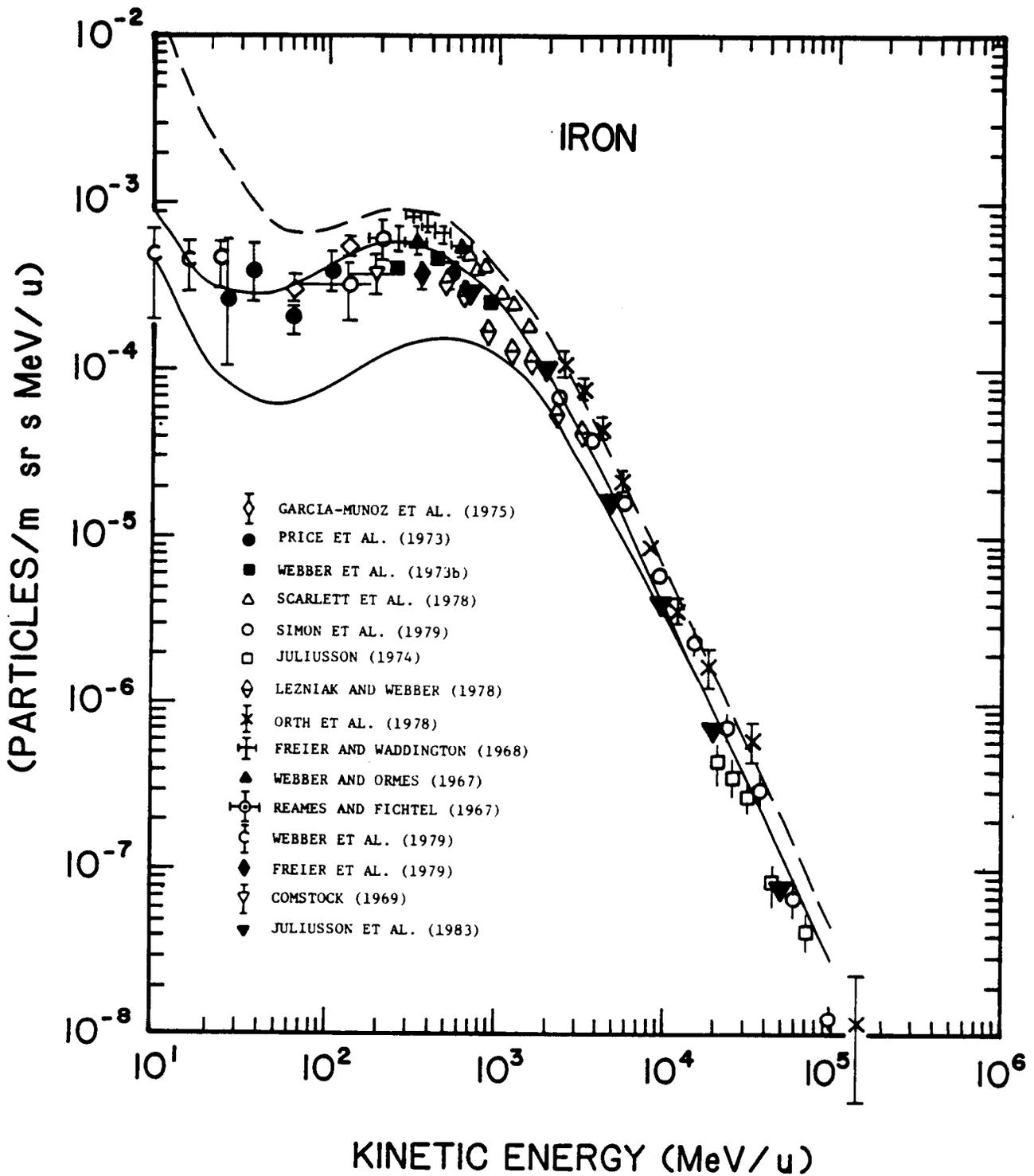


Figure 1. The cosmic ray iron spectrum: The solid curves are for solar maximum (lower) and solar minimum (upper). The dashed curve is the 10% worst case iron spectrum, which is implied by comparison with the cosmic ray helium spectrum. (This figure is taken from ref. [14], refer to this report the references to the data in this figure.)

To describe the cosmic ray spectra at other phases of the solar cycle, we linearly interpolate between the solar maximum and solar minimum spectra with an interpolation factor that is a sinusoidal function of time. The period of

this sine function is set by the sun spot cycle and the phase is adjusted to match the cosmic ray neutron monitor data. Since the actual solar cycle is a poor fit to a sine wave, this method of fitting leads to a factor of 2 uncertainty in predicting future flux levels below 1000 MeV/amu. This is the dominant source of error in the model for galactic cosmic rays. There is little point in improving the spectral fits or the elemental ratio fits so long as we have no better way to predict future levels of solar modulation.

4.0 Intensity Fluctuations at Low Energies

The galactic cosmic ray model discussed above describes the particle intensity during quiet periods at any point in the solar cycle. It often occurs that solar or interplanetary disturbances add to the particle intensity at earth. To account for this we used data from the Univ. of Chicago experiment on IMP-8, [15], to determine a flux level at each energy for the elements H and He, such that the flux measured on IMP-8 exceeded this level only 10% of the time. From these flux levels, we constructed a 10% worst case spectrum for H and He. There was not enough statistical precision in the Fe data from IMP-8 to determine 10% worst case flux levels for Fe, so we assumed that the fluctuations in the Fe spectrum were the same fractional size as those in the He spectrum. This 10% worst case spectrum is shown as the dashed curve in figure 1. The instantaneous Fe flux at any energy should exceed this spectrum only 10% of the time.

5.0 Solar Energetic Particles

The largest increases above the galactic cosmic ray background are due to solar energetic particle (SEP) events, produced by solar flares. For SEP's, the data base on protons is much more extensive and covers a much longer time period than the data on heavy ions. Because of this, we adopted the strategy of modeling the proton differential energy spectra in SEP's and then using the heavy ion to proton ratios to construct the heavy ion spectra. This procedure is not very satisfactory since heavy ions are often found to have different spectra than protons in the same SEP. It is justified only because: 1) the variability in proton flux from one SEP to another is greater than the variability in the heavy-ion-to-proton ratio, and 2) the chronology of well measured proton spectra is four times longer than the one for heavy ion spectra and more complete as well. The proton data, therefore, provide a better description of the variability in SEP size. We followed the method of King[16] to model the proton differential energy spectra in SEP events. Following King, we defined large SEP events as ones with one week integral proton fluences (above 10 MeV) exceeding 2.5×10^7 protons/cm². We also treated the August 1972 SEP's as a special case, as King had done. By using integral measurements of the peak proton flux and total proton fluence above three energy thresholds, we constructed proton differential energy spectra. These spectra were constructed for the peak flux and the total event fluence in three cases: 1) using the means of the log. normal distributions of the peak fluxes and total fluences, we constructed spectral models for large SEP's; 2) using these same means + 1.28σ (to reach the 10% probability level in the log normal distributions), we constructed 10% worst case spectral models for large SEP's; 3) Using the published data on the SEP of Aug. 4, 1972, we constructed spectral models for this event, which we called an anomalously large event, as King had done. The 10% worst case spectral models are intended to provide flux and fluence estimates so high that only one large SEP in 10 will produce a peak flux or a fluence that exceeds this model. Following the publication of additional data on SEP's by Chenette and Dietrich[17] and others, the models for the peak SEP fluxes were revised[14].

The heavy ion to proton ratios we adopted were the means of the ratios of individual SEP events that we found in the published data. These mean ratios were used to define spectra for mean SEP composition. We also constructed distributions of these ratios and found that they looked like two half-gaussians (with different standard deviations), joined at the mean. The tail of this distribution was broader toward the heavy ion rich side than toward the heavy ion poor side. We used this distribution to determine heavy ion to proton ratios so large that they should be exceeded by only one SEP in 10. These ratios were used to define spectra with 10% worst case heavy ion enrichment. This work was also updated in ref. [14]. The mean ratios we have adopted are close to those in a recent survey by Mason[18].

6.0 The Anomalous Component

This is a steady feature of the low energy spectra of He, N, O, Ne and Ar. There is some evidence for it in the spectra of C, Mg, Si, and Fe. At the earth's orbit (1 astronomical unit or AU), it exceeds the cosmic ray background only during solar minimum. Even then, it makes a minor contribution to the integral LET spectrum. We have used the published measurements of the anomalous component spectra near 1 AU to produce analytic models of these spectra for the elements He, N, and O in the interplanetary medium.

If the anomalous component is singly ionized as the theory of Fisk et al.[19] suggests, then these ions would have greater access to the inner magnetosphere of the earth. We have included this possibility in our model for the anomalous components of the elements He, C, N, O, Ne, Mg, Si, Ar, and Fe.

The intensity of the anomalous component increases at ~15%/AU with radial distance from the sun. This means that in the outer heliosphere, the anomalous component always exceeds the galactic cosmic ray background and is a major contributor to the LET spectrum at solar minimum.

7.0 Material and Geomagnetic Shielding

The CREME model includes provisions for computing a geomagnetic cutoff transmission function, so that the orbit-averaged particle spectra can be modeled for any spacecraft in any orbit about the earth. This is done by sampling the vertical geomagnetic cutoff at a large number of points along the spacecraft's flight path, and then constructing the transmission function from this sample[20].

The model also computes the differential energy spectra inside the spacecraft. This is done by accounting for energy loss and nuclear interactions in the shielding. The method accounts for ions lost in interactions, but not for the products of those interactions that continue into the spacecraft. This leads to a systematic underestimate of the particle flux, but this underestimate is less than a factor of 2 for shielding of less than 50 g/cm² aluminum equivalent. More detailed calculations, which include secondary production are possible, but do not seem to be warranted.

8.0 Computation of LET Spectra

The model differential energy spectra for all the elements, propagated into the spacecraft to the depth of the microelectronic components, are combined to form a single integral LET spectrum[14]. The LET spectrum is simply,

$$F(L) = \int_L^{\infty} \sum_{j=1}^{92} (dN_j/dE) (dS_j/dE)^{-1} dS$$

Where,

$$S_j = dE/dx \text{ for an ion of atomic number } j.$$

Using the CREME model, the integral LET spectrum can be calculated inside any spacecraft in any orbit of the earth or in interplanetary space near the orbit of the earth. This can be done for a variety of interplanetary "weather" conditions and for any part of the 11 year solar cycle.

9.0 UNCERTAINTIES IN THE CREME MODEL

There are several deficiencies in the data base on the energetic particle environment near earth which affect the estimation of single event effect rates. The ionization state of heavy ions in the interplanetary medium strongly affects their access to the earth's magnetosphere. There is no conclusive direct evidence on these charge states above ~1 MeV/amu. In the case of galactic cosmic rays, there is no doubt that they have passed through about 7 g/cm² of interstellar gas. This is more than enough matter to fully ionize all but the very heaviest ions[21]. The theory of Fisk et al.[19] for the origin of the anomalous component predicts that it is singly ionized. There is some indirect evidence that the anomalous component is singly ionized. Several attempts are underway to measure the charge state directly, using the earth's magnetic field. One of these experiments reports preliminary results that favor higher ionization states[22,23]. The charge state of solar energetic heavy ions is also uncertain. Here too, the indirect evidence[24] indicates that that these ions are less than fully ionized. This evidence is consistent with the distribution of charge states measured at low energies[25].

For satellites passing through in the inner Van Allen belt, there is uncertainty about the contribution of trapped radiation to the SEU rate. If there is even a small admixture of heavy ions trapped along with the protons in the inner belt, these heavy ions could be the dominant cause of SEU's. The data base on trapped heavy ions has been reviewed [26] and it is not possible to rule them out as a dominant source of SEU's in the heart of the inner belt.

10. CONCLUSIONS

The CREME model provides a description of the radiation environment in interplanetary space near the orbit of the earth that contains no major deficiencies. The accuracy of the galactic cosmic ray model is limited by the uncertainties in solar modulation. The model for solar energetic particles could be improved by making use of all the data that has been collected on solar energetic particle events.

There remain major uncertainties about the environment within the earth's magnetosphere, because of the uncertainties over the charge states of the heavy ions in the anomalous component and solar flares, and because of trapped heavy ions.

The present CREME model is valid only at 1 AU, but it could be extended to other parts of the heliosphere. There is considerable data on the radiation environment from 0.2 to 35 AU in the ecliptic plane. This data could be used to extend the CREME model.

As the electronic and biological effects of intensely ionizing particles are better understood, it is reasonable to expect that LET will no longer provide an adequate description of the radiation. It is therefore important to provide models that contain a complete description of the radiation environment.

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