SINGLE EVENT UPSETS CAUSED BY SOLAR ENERGETIC HEAVY IONS

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Abstract

We calculate single event upset (SEU) rates due to protons, alphas, and heavier ions in two satellite systems for the major solar particle events of 1989-92, using a new and complete analysis of GOES proton data and high-energy heavy-ion fluences from the University of Chicago Cosmic Ray Telescope on IMP-8. These measurements cover the entire range of energies relevant to SEU studies and therefore overcome shortcomings of previous studies, which relied upon theoretical or semi-empirical estimates of high-energy heavy-ion spectra. We compare our results to the observed SEU rates in these events. The SEU rates in one device (AMD 93L422s on LEASATs) were overwhelmingly dominated by protons. However, even after taking into account uncertainties in the ground-test cross-section data, we find that at least ~45% of the SEUs in the other device (Fairchild 93L422s on TDRS-1) must have been caused by heavy ions. Our results demonstrate that *both* protons *and* heavy ions must be considered in order to make a reliable assessment of SEU vulnerabilites. Furthermore, the GOES/Chicago database of solar particle events provides a basis for making accurate solar particle SEU calculations and credible worst-case estimates. In particular, measurements of the historic solar particle events of October 1989 are used in "worst week" and "worst day" environment models in CREME96, a revision of NRL's Cosmic Ray Effects on MicroElectronics code.

I. Introduction

Large solar particle events (SPEs) pose occasional but severe radiation hazards for many space-based systems. Such events accelerate heavy ions (atomic number $Z \geq 2$) as well as protons to high energies. Early attempts to model the heavy-ion component of the SPE environment [1] were almost entirely based on observations at low energies (typically ~1 MeV/nucleon), far below the ~50-100 MeV/nucleon required to penetrate the typical minimum shielding of satellite electronic systems, and extrapolated to higher energies using proton spectra. Heavy-ion environment models using such extrapolations have proven to be notoriously unreliable. In fact, early models predicted SEU rates so far above what has actually been observed in space-based systems, that many designers have chosen to ignore the heavy-ion component of SPEs.

Another justification for ignoring solar heavy ions came from several analyses [2], [3], [4] of SEUs in the Fairchild 93L422 chips of the TDRS-1 Attitude Control System (ACS) during the historic SPEs of September-October 1989. These authors reported that their calculated proton-induced SEU rates could essentially account for all of the observed upsets, thus confirming the "common wisdom", that solar heavy-ions were a negligible source of SEUs. However, the proton-induced SEU cross-section for this particular device is very poorly determined. The cross-section measurements have large, poorly-understood systematic errors, particularly in the critical range below ~50 MeV. The standard Bendel 2-parameter fit for this device, which all of these authors used in their calculations, is also very poor, with a mean fit error of 44.3% [5]; the actual error could be even larger, since the fit does not give a particularly good account of the energy-dependence of the cross-section measurements. When one takes into account these cross-section uncertainties, the TDRS-1 rates certainly allow the possibility of a substantial heavy-ion contribution to the observed SEU rate.

Croley et al. [6] made the first attempt to investigate the October 1989 heavy-ion SEU rate on TDRS-1. From their model of the heavy-ion fluences, they concluded that roughly two-thirds of the observed SEUs were due to $Z \geq 6$ heavy ions. However, their model was based on particle measurements from Galileo which did not begin until late in the episode, after ~60% of the high-energy particle fluence had passed. For the bulk of the October 1989 fluence, their heavy-ions were scaled from low-energy GOES-7 proton observations[1]. Moreover, the Galileo heavy-ion measurements were still not at energies sufficiently high to penetrate the TDRS-1 shielding: the effective minimum shielding (corresponding to only 1% of the solid angle surrounding the ACS) is ~100 mils of aluminum. The minimum energy needed for an oxygen ion to penetrate this thickness is 47 MeV/nucleon (85 MeV/nucleon for iron); the maximum energy observed on Galileo, however, was only 44 MeV/nucleon for oxygen (64 MeV/nucleon for iron). The Croley et al. SEU calculations are therefore sensitive to the spectral shape they *assumed* in extrapolating to higher, directly-relevant energies.

In this paper we present new calculations of solar par-

[1]Croley et al. say they used the >3 MeV proton channel on GOES-7 for this purpose. However, there is no >3 MeV proton channel on GOES-7. We presume that they used the >5 MeV channel.

ticle SEU rates, including contributions from protons, alphas, and heavier ions. The most important feature of these calculations is a new and complete analysis of heavy-ion fluence measurements from the University of Chicago's Cosmic Ray Telescope on IMP-8 [7] for all the major solar particle events of 1989-92. The Chicago/IMP-8 instrument measures heavy ions over the full range of energies relevant for SEU studies, making our results independent of theoretical or semi-empirical assumptions about the high-energy heavy-ion spectrum. We compare our calculations to observed SEU rates in two devices, Fairchild 93L422s on TDRS-1 and AMD 93L422s on LEASATs, which have significant differences in their SEU cross-sections.

This paper is organized as follows. Section II reviews the particle environment data used in our calculations. Section III briefly summarizes the observed SEU data from TDRS-1 and LEASATs. Section IV presents the SEU cross-section ground-test data, and Section V explains our SEU calculation techniques. Our results are presented in Section VI. In Section VII we discuss our results and present our conclusions.

II. Particle Environment Data

A. Chicago/IMP-8 Heavy Ion Observations

The University of Chicago's Cosmic Ray Telescope [7] aboard the IMP-8 spacecraft has provided nearly continuous monitoring of the high-energy particle environment in near-Earth interplanetary space since its launch in October 1973. The telescope comprises three silicon detectors (labeled D1-D3) and a CsI scintillator (labeled D4). The telescope is primarily designed to measure heavy ions with atomic number $Z > 2$, covering an energy range of 25.3-208 MeV/nucleon for oxygen ions (47.1 - 430 MeV/nucleon for iron ions). In addition, a sapphire Cerenkov radiator at the bottom of the telescope extends the particle measurements up to ~1 GeV/nucleon in the very largest solar particle events (SPEs). The telescope also yields proton and alpha count rates, but the determination of these rates is complicated by the on-board priority scheme, which preferentially reads out heavy ions during high-rate periods.

The combined thickness of detectors D1-D3 at the front of the telescope is ~100 mils aluminum-equivalent, roughly the typical minimum shielding of electronic devices in spacecraft. For the purposes of this study, major SPEs of 1989-92 were therefore identified as an increase in the heavy-ion rate in the D4 detector, corresponding to a minimum flux of ~2.5 CNO nuclei/(cm^2-sr-day) at ~52-86 MeV/nucleon. Twenty-five SPEs satisfied this criterion, and the start- and end-times used for their fluence accumulations are listed in Table 1. Note that we have subdivided extended episodes (such as August 1989, October 1989, May 1990, June 1991), which showed a number of distinct increases, into separate events for the fluence analysis[2]. For each of these SPEs, the observed rates were fully corrected for dead-time, telemetry gaps, and other detection inefficiencies, to produce absolute particle fluences, with typical uncertainties (statistical + systematic) of ~10-20%[3]. The differential spectra of C, O, and Fe were generally determined in at least six energy bins, and fluences of other elements (N, Ne, Mg, Si, S, Ar, and Ca) were also determined in one or two energy bins, as statistics allowed[4]. Wherever possible, we have cross-checked our fluences with results from other instruments at lower and overlapping energies.

TABLE I
Major Solar Particle Events 1989-92

Event No.	Start Time (UT)	End Time (UT)
1	11 Mar 89 0200	13 Mar 89 1300
2	17 Mar 89 1900	19 Mar 89 2000
3	12 Aug 89 1700	15 Aug 89 0400
4	16 Aug 89 0100	17 Aug 89 0700
5	17 Aug 89 0700	19 Aug 89 1900
6	19 Aug 89 1900	20 Aug 89 2100
7	29 Sep 89 1100	03 Oct 89 2100
8	19 Oct 89 1300	20 Oct 89 1300
9	20 Oct 89 1300	21 Oct 89 0800
10	22 Oct 89 1800	24 Oct 89 1800
11	24 Oct 89 1800	27 Oct 89 2300
12	29 Oct 89 0400	01 Nov 89 2400
13	15 Nov 89 0700	16 Nov 89 2400
14	30 Nov 89 1500	02 Dec 89 1300
15	21 May 90 2200	24 May 90 0400
16	24 May 90 2100	26 May 90 2200
17	26 May 90 2200	28 May 90 0600
18	28 May 90 0600	31 May 90 0100
19	23 Mar 91 0900	28 Mar 91 2200
20	05 Jun 91 1200	10 Jun 91 2400
21	11 Jun 91 0300	14 Jun 91 0100
22	15 Jun 91 0900	18 Jun 91 2300
23	25 Jun 92 2200	27 Jun 92 2300
24	30 Oct 92 1900	02 Nov 92 0400
25	02 Nov 92 0400	05 Nov 92 2300

As an example, Figure 1 shows the event-integrated iron and oxygen fluences for the 24 October 1989 SPE from the Chicago/IMP-8 instrument (circles), the Goddard VLET instrument on IMP-8 [8] (squares), and the Caltech Heavy Ion Counter (HIC) on Galileo [9] (triangles).

[2]For subsequent comparisons with SEU rate data, some of these events are re-combined, because of statistics or the extended time interval covered by the SEU reports. Not all of the periods in Table 1 showed significant increases in the TDRS-1 SEU rate (see Section VI below), and the TDRS-1 SEU database showed no periods of significant increase in 1989-92 which are not included in Table 1.

[3]The one major exception to this statement is the 20 October 1989 event, which was produced by a powerful interplanetary shock passing Earth. In this case, problems associated with the very high rates in the telescope left a factor of two systematic uncertainty in the fluences.

[4]In subsequent modeling, these elements were assumed to have the same spectral index as oxygen. Also, for completeness, rarer $Z > 8$ elements which were not directly measured by the Chicago instrument were scaled from the oxgyen spectrum using the relative abundances given by Croley et al. [6]. Of course, these very rare species made negligible contribution to the calculated SEU rates.

The figure also shows power-law fits (solid lines), which we use in subsequent modeling, since they give good descriptions of the fluences throughout the high-energy range relevant to SEU studies. In this event (and many other very large SPEs), the iron spectrum is significantly harder than the oxygen spectrum. Also, these power laws continue – without evidence of any roll-off – up to ~1 GeV/nucleon or until they intersect the expected galactic cosmic ray (GCR) background (shown by the short-dashed curves, with normalization fixed by the oxygen datapoints above ~500 MeV/nucleon).

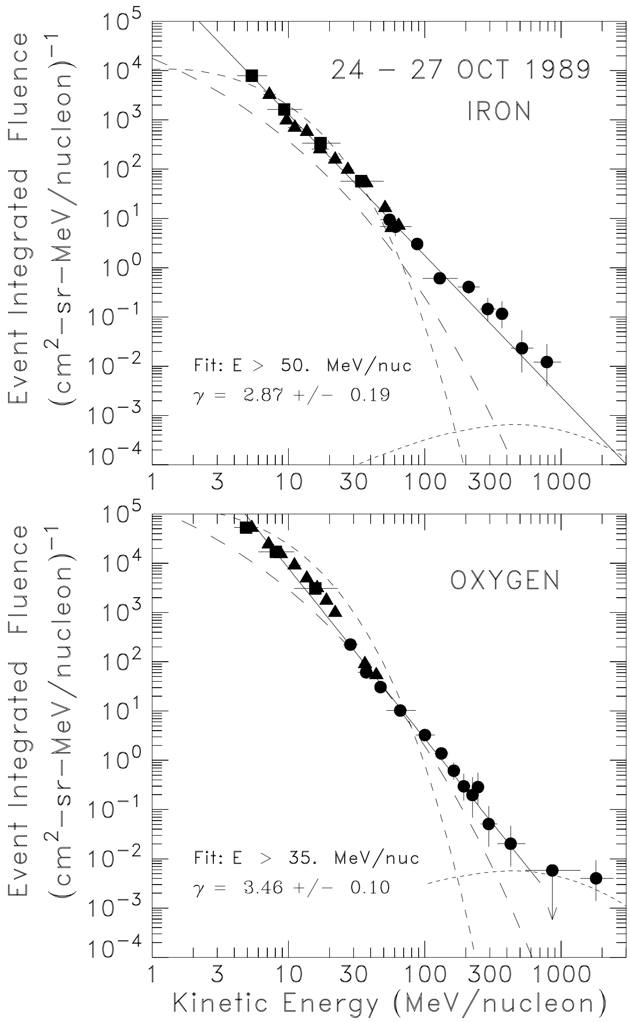

Fig. 1. Iron and oxygen fluence measurements and models for the 24 October 1989 solar particle event. See text for details.

This absence of a high-energy roll-off is an important feature of the Chicago/IMP-8 fluences which other solar particle models, based on extrapolations from lower energies, do not reproduce. Also shown in Figure 1 are model spectra for this event from Croley et al. [6] (intermediate-length dashes) and MACREE [10] (long dashes)[5]. The potential consequences of this shortcoming are illustrated in Figure 2, which shows the LET spectrum produced by these models after transport through the TDRS-1 shielding distribution [11]. At LET ~1 MeV-cm^2/mg, the models are comparable to the results given by the Chicago/IMP-8 fluences and will produce essentially the correct SEU rates for low-threshold devices, such as the TDRS-1 93L422s. However, in devices with high thresholds (LET ~20 MeV-cm^2/mg), these models may underestimate the SEU rate by an order of magnitude or more[6].

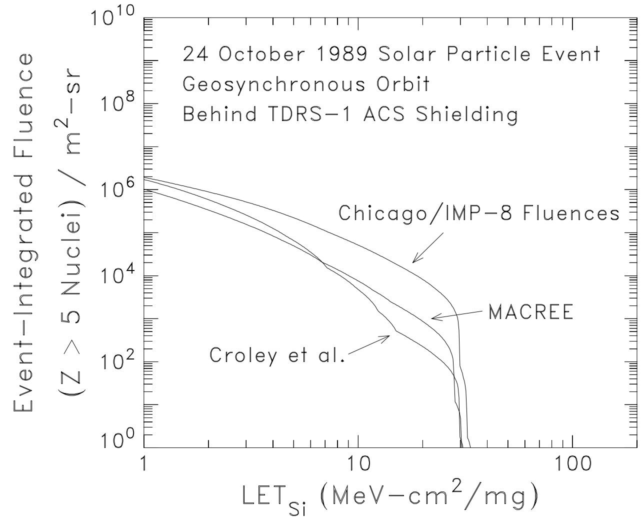

Fig. 2. Integral LET spectra in geosynchronous orbit behind the TDRS-1 shielding distribution, as calculated for the 24 October 1989 event, using the Chicago/IMP-8 fluences and the MACREE and Croley et al. models. This calculation included only nuclei with $6 \leq Z \leq 30$, since other elements are not specified by the Croley et al. model.

B. GOES Protons and Alphas

We determined the proton fluences for the SPEs of Table 1 from the seven fully-corrected integral channels (> 1 MeV to > 100 MeV) of the MEPAD instrument on GOES-7. To constrain the proton fluences at higher energies, we also used data at 355-685 MeV from the HEPAD instrument on GOES-6, corrected for backward-going particles, data gaps, and the GCR background as determined from temporal sidebands [12]. We fit the integral spectra to exponentials of a third-order polynomial in rigidity, which was used simply because it gives a very good empirical description of the data over the entire energy range. As examples, the datapoints and fitted curves for three SPEs are shown in Figure 3.

Finally, we modeled the alpha fluences in these SPEs using the spectral indices from the Chicago/IMP-8 carbon and normalization determined by the GOES-7 alpha channel at 15-45 MeV/nucleon. Since solar energetic alphas and carbon ions have very nearly the same charge-to-mass ratio [13], their spectral shapes should be very similar. However,

[5] Specifically, we followed the prescription given by the MACREE authors: the curves were calculated using a differential spectrum of the form $KE^{1/4}\exp(-gE^{1/4})$, with g=5.70 and normalization K determined by the GOES alpha fluences. Abundances of heavier elements relative to He were then set to one-quarter of the values used in CREME [1], independent of energy.

[6] This discrepancy between MACREE and the Chicago/IMP-8 fluences is reduced to only a factor of ~3 when the *entire* October 1989 series of events is considered.

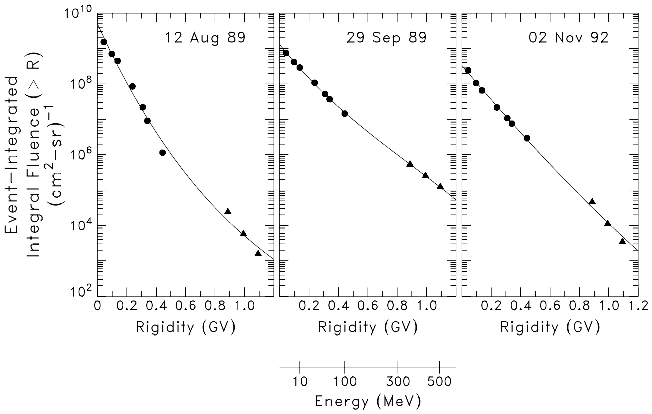

Fig. 3. Proton integral fluences versus rigidity for three SPEs. The circles are MEPAD/GOES-7 datapoints; the triangles from HEPAD/GOES-6. The additional horizontal scale in the middle panel shows the correspondence between rigidity and kinetic energy.

the relative abundance of alpha particles can show event-to-event variability [14], thereby necessitating the normalization to the GOES data. Although the GOES alpha measurements extend up to ~100 MeV/nucleon, possible backgrounds in the high-energy channels have not been thoroughly studied. Pending further analysis, we believe that the shape of the high-energy alpha spectrum is more reliably determined from the Chicago carbon data.

III. SEU Data from TDRS-1 and LEASAT

Several authors have previously explained how SEUs are reported from TDRS-1 [15], [3], [6]. On TDRS-1 (deployed in geosynchronous orbit in April 1983), the Attitude Control System (ACS) RAM contains eight Fairchild 93L422 1024-bit microchips, organized into four "pages". Determining the SEU rate in this system is complicated by the manner in which the memory is organized and SEUs are monitored. Near-real-time SEU detection is provided 1096 bits, mostly on "page 2", which are monitored by a checksum algorithm which immediately logs SEUs in telemetry to the ground. Whenever possible, we have determined the SEU rates from "page 2", which provides finer time resolution because of the checksum monitor and because the unused portion is dumped more frequently during high error-rate periods. To increase statistics in low-error rate periods, however, we also examined the unused portions of other pages (an additional ~3.2 chips), which are usually dumped weekly but sometimes more often during high error-rate periods. Since the number of chips used in determining the SEU rate was variable, we report the observed rate in SEUs/chip. Our rates agree very well with those extracted in previous studies [2], [3], [4], [6].

Determining SEU rates on the LEASAT [16] satellites is considerably more straightforward. The SEU rates come from two satellites (F2 and F5), both deployed in geosynchronous orbit. AMD 93L422 1024-bit chips are used as RAM, with ~13.0 chips on each satellite otherwise free and available for SEU monitoring. SEU rates are determined from daily dumps, and the rates on the two satellites generally show good agreement. These LEASATs have provided nearly continuous SEU reports since December 1989. There are some datagaps in the SEU record, the most significant of which is for the very large SPE of 23 March 1991: the procedure for extracting SEU rates from the dumps is apparently not fully automated, and the report for this event is simply "too many".

IV. SEU Cross-Sections

Ground tests have shown that the Fairchild and AMD 93L422s have different SEU cross-sections. We obtained heavy ion and proton cross-sections for both devices from the published literature [19], [20], [22], [17], [23], [24], supplemented with a few unpublished measurements [25]. Figure 4 shows the available data[7] on heavy-ions (top panels) and on protons (bottom panels) for both the Fairchild (left panels) and AMD (right panels) devices. These datapoints have generally been published without error bars, implying that statistical uncertainties are typically less than 10%. However, the sizable spread among the datapoints suggests that the measurements also have non-negligible and difficult-to-assess systematic errors, especially near threshold. Variation among devices in the same manufacture lot is typically on the order of 15%, and the device characteristics may be changed from time to time by the manufacturer. Another source of inconsistent results may be in the systematics of beam diagnostics, including the calibration of the beam monitor and non-uniformity of intensity across the beam.

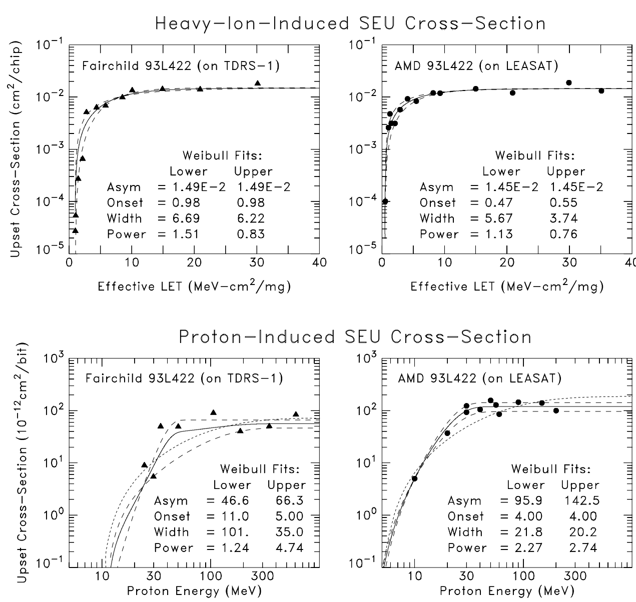

Fig. 4. Experimental SEU cross-section measurements and fits. Parameters are for the bounding Weibull distributions, shown as long-dashed curves. The solid curves are averages of the bounding Weibull distributions. The short dashes in the bottom panels are Bendel 2-parameter fits. (See text.)

[7] We have not included the measurements of Criswell et al. [26], which are suspect due to possible contamination from reaction products in the beam degraders [27].

To reflect this spread in the cross-section measurements, we selected subsets of the datapoints in each panel and fitted two Weibull distributions [18], which together provide a reasonable envelope around the cross-section measurements. We then used these two bounding Weibull distributions, shown as long-dashed curves in Figure 4, to calculate upper and lower limits on the SEU rates which reflect the systematic uncertainty due to the cross-section data.

For comparison, also shown in the bottom panels of Figure 4 are the Bendel 2-parameter [21], [5] fits[8]. To our knowledge, there is no theoretical reason for preferring either functional form for the proton cross-section curves. We used the Weibull distribution simply because it gives a better empirical description of the cross-section data.

The top panels of Figure 4 show that the heavy-ion cross-sections for the Fairchild and AMD devices are very similar, except that the AMD device apparently has a lower threshold and is systematically larger at linear energy transfer (LET) below $\sim$ 10 MeV-cm^2/mg [17]. The proton cross-section of the AMD device is substantially larger at all energies. As we show below, these differences in the SEU cross-sections are readily apparent in the overall SEU rates and relative importance of proton and heavy-ions on TDRS-1 and LEASAT.

V. SEU Calculation Techniques

For each solar particle event, we used the fits of the interplanetary particle fluences as described above in Section II. Since TDRS-1 and LEASAT are in geosynchronous orbits, no correction for geomagnetic transmission was necessary. We then used a nuclear transport code [28] to transport these particle fluences through the actual TDRS-1 [11] and LEASAT [17] shielding distributions (as determined by ray-tracings through detailed satellite mass models), since careful treatment of the shielding distribution – as opposed to a simple mean or uniform shielding thickness – is needed for accurate SEU calculations for SPEs [4]. This transport code utilized standard energy-loss formulae [29],[30],[31] and also accounted for nuclear fragments produced in the shielding [32], although fragmentation is admittedly a small effect except through the thickest parts of the shielding distribution.

To calculate proton-induced SEUs, we numerically integrated the product of the omnidirectional differential fluence and the energy-dependent SEU cross-section [20]. We checked that our software reproduced calculations of the TDRS-1 proton SEU rates previously reported by other authors [2], [3], [4] when we used their shielding distributions and cross-section parametrizations[9].

To calculate heavy-ion-induced SEUs, we used the standard rectangular parallelpiped (RPP) method, which convolves the integral LET spectrum with the differential distribution of chordlengths through the sensitive volume of the device [18],[33]. For both the Fairchild and AMD 93L422s we used RPP dimensions of 38 μm $\times$ 38 μm $\times$ 2 μm, consistent with the cross-section plateau of $\sim$1450 μm^2/bit in Figure 4 and photomicrographic examinations of the device[10].

Our calculations also included a numerical integration over the LET-dependent SEU cross-section (as given by the Weibull fits in Figure 4), since proper handling of this threshold region in the cross-section data is especially important for accurate results in solar particle events. We confirmed that our software reproduced the heavy-ion SEU rates calculated by Croley et al. [6] to within less than 1% when we used their fluence model and cross-section curve[11].

One detail of our heavy-ion calculations is worth particular mention. In calculating the LET spectra, we included only $Z \geq 2$ ions whose energy *after passing through the shielding* is above 10 MeV/nucleon. At lower energies, ions can come to rest along the longest chords of the sensitive volume. A fundamental assumption of the standard RPP formalism[12] is that the ion's LET does not change as it traverses the sensitive volume [18]. With this assumption, the formalism calculates the deposited energy by simply multiplying the ion's dE/dx at the surface of the sensitive volume by the chordlength. When an ion comes to rest in the sensitive volume, especially along a very long chord, its energy deposition – and hence its ability to cause an SEU – can be greatly overestimated. The resulting overestimate can be particularly large in the case of low-energy alphas[13]. Since we are neglecting ions with energy below 10 MeV/nucleon, strictly speaking, our calculations should be considered a *lower limit* on the heavy-ion-induced SEU rates. However, we estimate that including $Z > 2$, $E < 10$ MeV/nucleon ions would increase the calculated

[8] A=9.39 and B=12.75 [5] for the Fairchild 93L422; A=4.88 and B=7.09 for the AMD 93L422.

[9] The proton SEU rates calculated by Croley et al. [6] for the October 1989 events on TDRS-1 are lower than those of all other authors. Part of the discrepancy comes for a factor-of-two error in their handling of the solid-angle factor. However, even after taking this error into account, a discrepancy remains. We have no explanation for this discrepancy, since Croley et al. also claimed to have used the GOES proton fluences and the standard cross-section parametrization.

[10] Croley et al. [6] used RPP dimensions of 51 μm $\times$ 51 μm $\times$ 2 μm. However, we found that the results presented here were relatively insensitive to the RPP dimensions.

[11] Our calculations differ from those of Croley et al. [6] in several technical details. In addition to the different RPP dimensions noted above, Croley et al. apparently used the TDRS-1 shielding distribution [11], based on a 6000-ray mass distribution analysis, in its original 466 bins. We handled the distribution in only 20 bins, selected from the 466 bins at 5% cumulative probability points. Also, Croley et al. determined the chordlength distribution through the 93L422 sensitive volume using an eight-million ray Monte Carlo on the JPL Cray Y-MP2E/322. We used an analytic formulation [34] implemented in a $\sim$40-line FORTRAN subroutine (DIFPLD, a part of the 1986 CREME suite of programs [1]) which quickly and accurately reproduces their results on a PC.

[12] Alternate formulations [35] do not make this assumption.

[13] Heavier ions can cause SEUs over many paths through the RPP; but alphas, because of their relatively low rate of energy deposition, can cause an SEU or *appear to cause an SEU in the standard formalism* only along the longest RPP chords. In large, thin devices like the 93L422, the longest RPP chords also correspond to highly oblique incidence angles, where the shielding due to other nearby devices, the circuit board, etc. can significantly attenuate the flux. This attenuation is not properly reflected in standard SEU calculation techniques, in which correlations between shielding thickness and directions through the RPP are ignored. Accurate calculations of SEU rates due to low energy solar alphas therefore require particular care and will be the subject of a future paper.

rates by no more than ~20%.

VI. Results

A. TDRS-1 Heavy Ion Rates

Figure 5 shows the observed SEU rates in the Fairchild 93L422s aboard TDRS-1 during the major solar particle episodes of 1989-92. Temporal sidebands have been used to subtract the contemporaneous GCR contributions; several of the events produced no significant increase in the TDRS-1 SEU rate. The figure also shows our calculated rates due to alpha particles and heavier ($Z > 2$) ions. The heights of the bars reflect the systematic uncertainty due to the cross-section, as discussed in Section IV. This systematic uncertainty is ~30% for the $Z > 2$ rates, but can be substantially greater for the alpha rates, since the cross-section uncertainty is larger at low effective LET.

Figure 5 also shows the observed weekly solar-quiet-time SEU rates on TDRS-1 at solar minimum (1 Sept. 1986 - 1 Sept. 1987) and solar maximum (1 February - 30 April 1990). These SEUs are due to galactic cosmic rays (GCRs), with protons and alphas contributing only a few percent to the total. Our calculated rates for these periods, which used the GCR model[14] of Nymmik et al. [36], agree with the observed rates to within the cross-section uncertainties, thus validating our heavy-ion SEU calculation techniques.

Figure 5 clearly shows that *even after allowing for the cross-section uncertainty*, heavy ions *must* account for at least ~45% of the observed SEUs on TDRS-1 during the September-October 1989 events. In other cases, such as the October-November 1992 events, heavy ions apparently account for a somewhat smaller proportion. The calculated heavy-ion SEU rate exceeds the observed rate in only one event (21 May 1990), for reasons which are not yet clear.

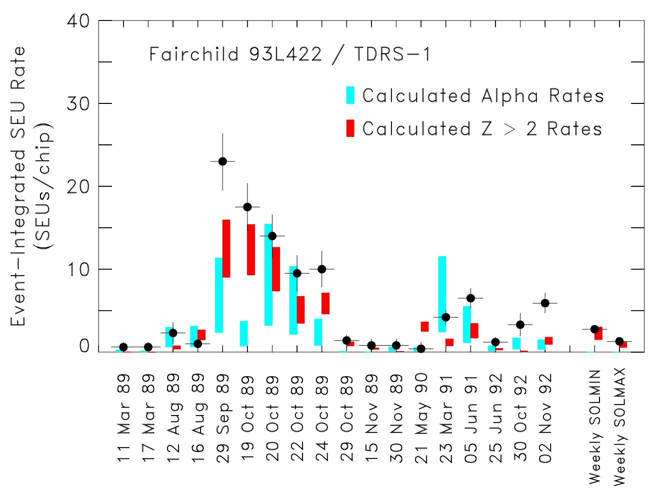

Fig. 5. SEU rates observed on TDRS-1, compared with calculations of alpha- (gray bars) and $Z > 2$ heavy-ion-induced rates (black bars). SPEs are labeled by their start dates from Table 1, except that events of 16-19 August 1989, of 21-28 May 1990, and of 5-11 June 1991 have been combined. See text.

[14]Using the old CREME GCR model [1] for solar mimimum and solar maximum – but not for these year dates – produced nearly identical results.

B. TDRS-1 Proton Rates

Figure 6 shows our calculated proton-induced SEU rates for these same SPEs[15]. The bars again reflect the large systematic uncertainty in the cross-section. The dashed lines in each bar show the results using the standard Bendel 2-parameter fit for this device [5]. As noted by previous authors [2], [3], [4], these calculated proton rates can by themselves essentially account for all of the observed SEUs in September-October 1989. However, the cross-section uncertainty makes this an exceedingly tenuous conclusion.

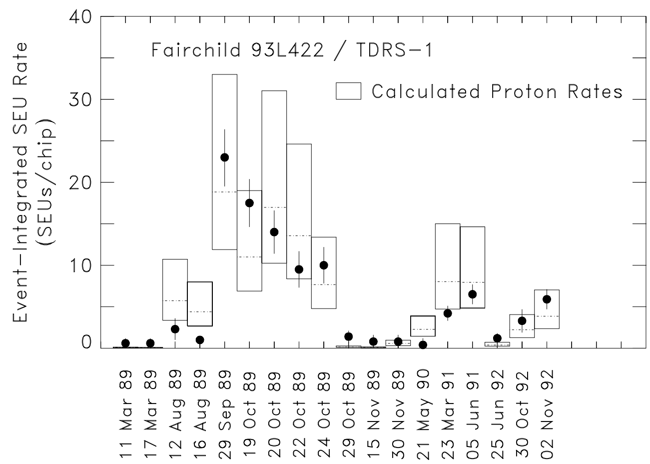

Fig. 6. Observed SEU rates aboard TDRS-1, compared with calculations of proton-induced rates.

Figure 7, which shows the proton spectra for several SPEs *after transport through the TDRS-1 shielding distribution*, explains why uncertainties in these calculated rates are so large. As is generally true for these large SPEs, these internal spectra have their maxima at ~20-50 MeV. The calculated SEU rate is dominated by the cross-section in this energy range, since the spectra fall off quickly at higher energies. Unfortunately, as shown in the bottom-left panel of Figure 4, ~20-50 MeV is where the cross-section for this device rises most rapidly and where the uncertainties in the ground-test data are therefore largest. Moreover, the 12 August 1989 and 23 March 1991 events, in which the calculated proton SEU rates most egregiously exceed the observed rates, have especially soft spectra above 50 MeV, making lower energies even more dominant in the rate calculation. This suggests to us that the reported cross-section values at ~20-50 MeV probably do *not* accurately represent the actual proton cross-section of the 93L422s aboard TDRS-1. The actual cross-section in this energy interval is much lower, and probably close to that given by our lower-bound Weibull distribution. Heavy-ions and

[15]In view of the observed SEU rates and calculations shown in this figure, we strongly disagree with the recent statement of Stassinopoulos et al. [37] that "The worst case flare of [solar] cycle 22 relative to generating SEUs is the October 30, 1992 event, rather than any of the 1989 flares, particularly the October 19, [1989] flare which was heretofore considered the worst event of cycle 22." (Stassinopoulos et al. combined the multiple increases of 19-27 October 1989 and of 30 October - 2 November 1992 events into single events.)

protons therefore contribute to the observed TDRS-1 SEU rates during solar particle events in roughly equal proportions.

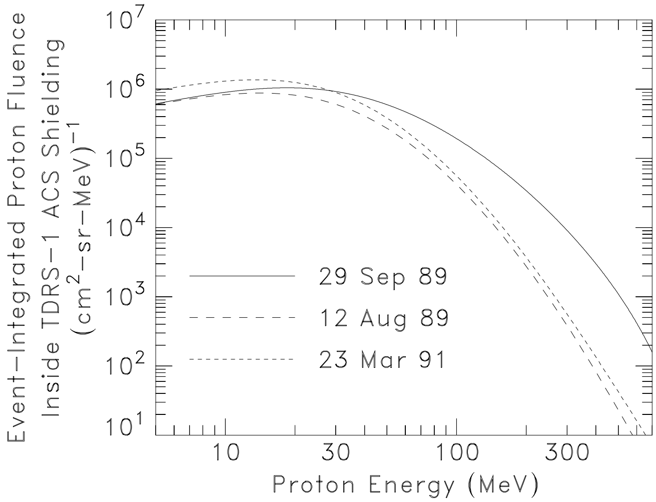

Fig. 7. Calculated proton fluence inside the TDRS-1 shielding for three solar particle events.

C. LEASAT

Figure 8 shows the reported SEU rates in the AMD 93L422s aboard LEASATs. Because the LEASAT rates are based on ~26.5 kbits (compared to ~2 - 5 kbits on TDRS-1), the statistical uncertainty on the LEASAT rates is only ~10%, even though these SPEs were much smaller than those of 1989. The calculated proton, alpha, and Z > 2 SEU rates are also shown. As noted in Section IV, the proton SEU cross-section for this device is substantially larger than for the TDRS-1 93L422s. Consequently, the observed SEU rates are higher here than in the same SPEs aboard TDRS-1, and protons clearly dominate the SEU rates.

In fact, Figure 8 suggests that the calculated alpha- and heavy-ion rates may be somewhat high in this case. Also shown in the figure are the weekly solar maximum (1 February - 30 April 1990) and solar minimum (1 September - 31 October 1995) SEU rates on LEASATs. The calculated GCR SEU rates in these periods are systematically higher than the observations by ~30-100%. GCR SEU rate calculations are relatively insensitive to details of the shielding distribution, and preliminary comparisons between the GCR model [36] and Chicago GCR fluxes show reasonable agreement. The actual heavy-ion cross-section for the on-orbit devices may therefore be a bit lower than shown in Figure 4. This discrepancy between the calculated and observed GCR SEU rate on LEASATs has been noted previously [17].

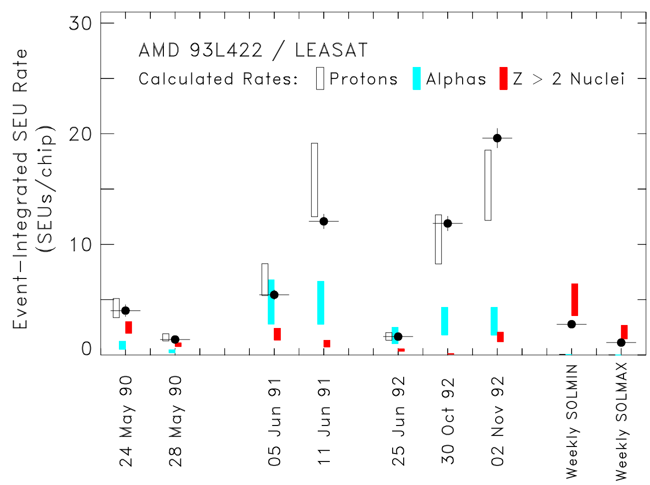

Fig. 8. Observed SEU rates aboard LEASAT, compared with calculations of proton- (white bars), alpha- (gray bars), and Z > 2 heavy-ion-induced rates (black bars). SPEs are labeled by their start dates from Table 1, except that the events of 24-26 May 1990 have been combined. Not shown are results for the events of 21 May 1990, 23 March 1991, and 15 June 1991, for which only partial SEU reports were available.

VII. Discussion and Conclusions

The SEU calculations presented above differ from those of previous authors in several important respects. First of all, we have included all abundant species, whereas previous studies have neglected heavy-ions [2], [3], [4] or alpha particles [6]. We also based our calculations on actual *measurements* of particle fluences over the *entire* range of energies relevant to SEU studies, without theoretical or semi-empirical assumptions [6], [10] about how the spectra extend from lower energies or how they may be extrapolated from lighter species. We have validated our heavy-ion calculation techniques by examining galactic SEU rates during solar-quiet periods. We have also made quantitative estimates of how uncertainties in the measured SEU cross-sections propagate to the SEU rate calculations.

All together, we have examined twenty-five SEU reports from major solar particle episodes in two different satellite systems. In only two cases (16 August 1989 and 20 May 1990, aboard TDRS-1) does our combined calculated SEU rate (that is, protons + alphas + Z > 2 heavy ions) exceed the observed rate by more than a factor of two. Moreover, we have plausibly argued that the systematic excess in the calculations can be attributed to the cross-section data (especially the Fairchild 93L422 proton cross-section). We have therefore shown that the GOES data and Chicago heavy-ion measurements together provide a basis for reliable calculations of the SEU hazard posed by solar particle events.

At least 45% of the SEUs on TDRS-1 during the September-October 1989 events were produced by heavy ions. A similar conclusion was advanced by Croley et al. [6] for the October 1989 events, although perhaps somewhat fortuitously, since their model does not accurately describe the particle fluences at energies relevant to TDRS-1 SEUs.

In fact, the Croley et al. model would not have given the correct SEU rates for a higher-threshold device or for a device which was more heavily shielded. However, given the careful treatments here of the complete particle environment, the TDRS-1 shielding distribution, and uncertainties in the cross-section data, this conclusion is now unassailable. Consequently, studies based on the *assumption* that protons dominated the TDRS-1 SEU rates during SPEs should be critically re-examined. Recommendations drawn from those studies should also be re-evaluated. In particular, the recommendation of Petersen et al. [18] that "the worst case calculations for a mission should include only the proton component of solar flares" should no longer be followed.

On the other hand, SEUs in the AMD 93L422s on LEASATs are clearly proton-dominated, with heavy ions providing only a minor component. This difference in the relative importance of protons and heavy ions in TDRS-1 and LEASAT emphasizes the need to consider *both* protons *and* heavy ions when evaluating SEU vulnerabilities posed by solar particle events.

We also reiterate a point previously noted by Smith [4], that careful modeling of the shielding distribution is critical to accurate solar particle SEU rate prediction. For example, in the case of TDRS-1, using a nominal shielding thickness of 100 mils instead of the actual shielding distribution overestimated the calculated heavy-ion SEU rates by factors which varied from SPE to SPE, but were typically ~5-10; using the mean TDRS-1 shielding thickness (~550 mils) instead of the actual distribution typically underestimated the heavy-ion rates by similar factors. One should therefore not expect to make reliable estimates of SEU rates during solar particle events without first investing in a reasonably good sector shield analysis. Given the variability in the spectral hardness and composition of solar particle events, attempts to "fit" the effective mean shielding of a system or device with an incomplete description of the particle environment [2], [37] are probably of limited value.

In the SEU rate calculations presented here, the largest source of systematic error is undoubtedly the cross-section data. Fortunately, the calculations also offer some guidance on where cross-section measurements are most critical for estimating solar-particle SEU rates. To the extent that the TDRS-1 shielding distribution may be considered "typical", proton cross-section measurements should be targeted at ~20 - 50 MeV, since these are the energies at which the proton fluence inside the shielding is highest in large SPEs. In the heavy-ion SEU calculations, the alpha rates have the greatest uncertainties. To reduce these uncertainties requires better cross-section measurements below 10 MeV-cm^2/mg. Well-determined RPP dimensions can also be especially important for the alpha-rate calculations.

A. Application to the CREME96 Software

This work has been undertaken as part of a NASA-sponsored effort to update NRL's Cosmic Ray Effects on MicroElectronics (CREME) code [1], which is widely used in evaluating SEU effects and serves as the basis of the environment model in other programs [35], [38], [10]. All of the software used in making the above calculations – including routines for the GCR model, energy loss, nuclear transport, and SEU rate calculations – are part of the revised code, known as CREME96. Other significant improvements, such as modeling of anomalous cosmic rays, solar particle ionic charge states [39],[13], and more accurate geomagnetic transmission modeling [40], are also included in CREME96.

CREME96 contains a complete revision of the solar particle model, based on the GOES and Chicago fluences described in this paper. In particular, the CREME96 offers two solar particle models, a "worst day of the solar cycle", based on the observed fluences of 20 October 1989, and a "worst week" model, based on 19-27 October 1989. These designations are based on the eleven-year TDRS-1 SEU database as well as the 23-year historical record of high-energy solar heavy-ion production from the Chicago/IMP-8 instrument. As noted by Majewski et al. [10], the 19-27 October 1989 sequence also qualifies as a "99% worst-case" event in the JPL solar flare model [41] for the model's three highest proton energies, 10, 30, and 60 MeV. (The proton fluence of the August 1972 event, on the other hand, is at the 99% level for 10 and 30 MeV, but not for 60 MeV. In any case, as previous (unsuccessful) modeling efforts have shown, the August 1972 event was probably not sufficiently well-measured to make a reliable and comprehensive SPE model for SEU studies.)

Of course, given that solar particle events can show considerable variability in terms of fluence, spectral hardness, and composition, what one considers "worst day" or "worst week" can also depend on other details of the SEU calculation, such as orbit, shielding, and device characteristics. In a future revision of the CREME code, we therefore intend to make available fluences for all major solar particle events in the 23-year Chicago/IMP-8 database. This database can then be used to make reliable, quantitative risk-assessment studies of how often a given SEU rate may be expected.

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