Observation of Solar Particle Events From CREDO and MPTB During the Current Solar Maximum

C. S. Dyer, K. Hunter, S. Clucas, D. Rodgers, A. Campbell, and S. Buchner

***Abstract*—Data obtained from the Microelectronics and Photonics Test Bed since July 2000 show a large number of solar particle events. Measurements from the Cosmic Radiation Environment Dosimetry Experiment show that the relative importance of proton and heavy ion fluxes varies greatly from event to event and even with time during an event. Single-event upsets in the analog-to-digital converter experiment are compared with calculations based on the measured fluxes; this demonstrates the importance of both contributions. Three major events show that the CREME96 worst-day model can be equaled in ions and exceeded in protons.**

***Index Terms*—Analog to digital converter, heavy ions, linear energy transfer spectra, protons, single event effects, solar particle events.**

I. Introduction

THERE are a number of published instances of enhanced rates of single-event effects (SEEs) during solar particle events (SPEs) in both operational and experimental space systems. The Tracking and Data Relay Satellite (TDRS-1) experienced mission-threatening single-event upsets in the Attitude Control System, and these were enhanced tenfold during the solar particle events of September and October 1989 [1]. The Solar Heliospheric Observatory (SOHO) has experienced SEEs in the power supply, service module, and various payloads [2]. These include both upsets and transients, some of which are mission threatening and some of which are related to SPEs. Large amounts of memory carried on the Microelectronics and Photonics Test Bed (MPTB) have shown greatly enhanced SEE rates during the SPEs of the current solar maximum, particularly during the Bastille Day event of July 14, 2000 [3]. Recently, the event of November 5, 2001 (proposed by the author to be the Guy Fawkes Day event in honor of the famous day in British history) has led to a serious anomaly in the Microwave Anisotropy Probe (MAP) spacecraft as a result of what appears to be a single-event transient [4].

Given the importance of these solar particle events, it is important to understand the sources of the anomalies and to use sensible worst-case models during design. For the latter, the CREME96 code [5] uses the solar particle events occurring during October 19–24, 1989. Ongoing data are needed to ensure that this model is worst case. In addition, there is a tendency to use this model to explain observed rates despite the fact that SPEs are hugely variable in intensity, spectral hardness, and composition. Also, there is frequently considerable controversy as to whether SEE rates are dominated by the nuclear interactions of the solar protons or by direct ionization by the ion component. The relative importance of these mechanisms will vary from event to event and with the device sensitivity. The only way to interpret observed SEEs is through the use of onboard monitors or extrapolation from monitors onboard other spacecraft. For the MPTB spacecraft, such monitoring was provided by the Cosmic Radiation Environment Dosimetry experiment (CREDO-3) [6], [7], and this enabled the observed SEU rates in 16-Mbit DRAMs during the Bastille Day event to be understood as resulting from considerable contributions from both mechanisms [3].

This paper extends the MPTB-CREDO data to July 2002. During this period, the Sun has shown a second peak of activity during late 2001 [8], and a number of large solar particle events have been observed by MPTB including the Guy Fawkes Day event, which rivals the events of July 2000 and October 1989.

II. CREDO-3 and MPTB

CREDO-3 is a miniaturized version of the CREDO series of experiments, which have flown on UoSATs, APEX, and STRV spacecraft. This version has been designed to provide environment dosimetry for the Microelectronics and Photonics Test Bed [3], which is aimed at space testing a number of advanced technologies in a radiation-stressing highly inclined (63°) elliptic orbit (39 200 $\times$ 1200 km). Results up to July 2000 and an instrument description have been presented in [6] and [7].

The proton telescope measures fluxes of protons of energy greater than 38 MeV, while the ion monitor measures linear energy transfer (LET) spectra in 16 channels, which cover the range from 100 to 20 000 MeV/(g cm^{-2}), with an upper channel providing an integral measurement above the higher level. These complementary measurements enable both proton-induced and ion-induced SEE to be quantified. Essentially continuous data coverage has been obtained from switch-on in November 1997 until July 2002 with the exception of a few periods of eclipses at around perigee and other minor data outages. Prior to July 2000, none of the observed solar particle events had approached the CREME96 levels, and no significant heavy ions increases had been observed beyond a linear energy transfer of 400 MeV/(g cm^{-2}) [6].

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C. S. Dyer, K. Hunter, S. Clucas, and D. Rodgers are with the Space Department, QinetiQ, Farnborough, GU14 0LX Hants, U.K. (e-mail: csdyer@space.qinetiq.com; kahunter@space.qinetiq.com).

A. Campbell is with the Solid State Devices Branch, Electronic Science and Technology Division, Naval Research Laboratory, Washington, DC 20375 USA (e-mail: campbell@ccf.nrl.navy.mil; artcampb@att.net).

S. Buchner was with SFA at the Naval Research Laboratory, Washington, DC 20375 USA. He is now with QSS Group Inc., Seabrook, MD 20706 USA.

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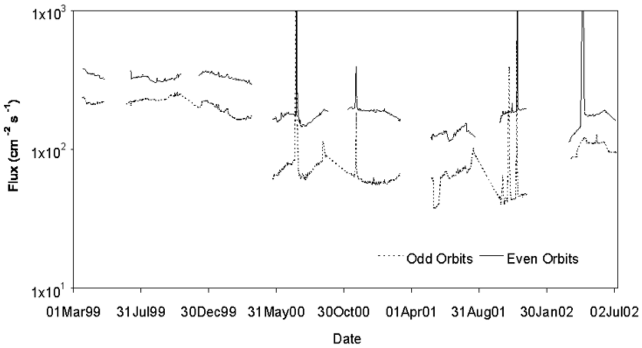

Fig. 1. Orbit-averaged proton fluxes for $E > 38$ MeV show the differing exposure to trapped protons between odd (lower plot) and even (upper plot) orbits and long-term changes due to the variation in height of perigee. Large solar proton events dominate the averages on certain days.

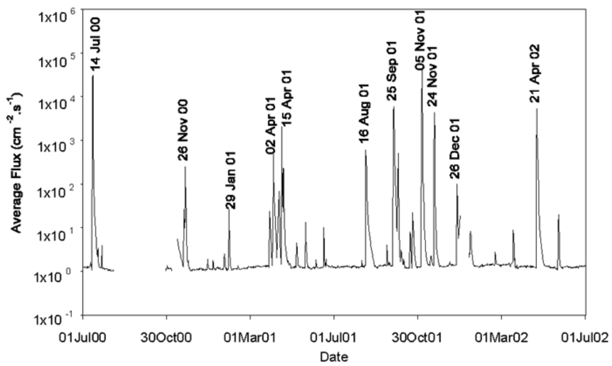

Fig. 2. Proton flux measurements for $E > 38$ MeV from CREDO-3 on MPTB taken outside of the inner radiation belt between July 2000 and July 2002 show cosmic-ray (protons and ions) modulation with a minimum intensity in August 2000, together with a number of very significant solar particle events. Note that the large event of November 9, 2000, was missed.

MPTB comprises 23 boards of test devices as well as the CREDO-3 monitor board. Results on upsets in the DRAM experiment have been presented in a previous paper [3]. Here we concentrate on upsets observed in the analog-to-digital converter (ADC) experiment, which comprises three AD9058 ADCs. This ADC is an 8-bit flash converter that uses a patented interpolating architecture to reduce the complexity of the device to only 128 comparators. Single events can occur in any functional area but are primarily due to interactions in the comparators or the interpolating latches. Additional details on the device, preliminary space results, and results of ground testing performed in support of this paper can be found in [9]. In general, SEUs in ADCs can result in a variety of output conditions, from those that do not matter in most applications and are just an additional source of noise, to those that cause functional errors along the logic path, to a string of incorrect conversions that last hundreds of clock cycles. In the work reported in this paper, we count single events when the conversion is outside of a noise window, independent of the nature of the error. For details of the error signatures, see [9].

III. Results

A. Time Variations of Proton Fluxes

The time variations in the average proton fluxes are presented in Figs. 1 and 2. Fig. 1 gives data for entire orbits, each of which includes two passes through the inner radiation belt. As discussed in [7], the even-numbered orbits experience more trapped protons than odd orbits. In order not to bias the averages, any orbit with missing data is excluded, leading to the gaps in the plots. The long-term trends are due to changes in the height of perigee (the higher the perigee, the lower the exposure). A number of solar proton events stand out even against the average trapped proton exposure. These stand out more clearly for the portions of the orbits outside of the inner proton radiation belt, as shown in Fig. 2 for the period from July 2000 to July 2002. The underlying level here is due to cosmic rays (both protons and ions) for which flux levels reached a minimum in August 2000 when they were a factor 2.4 lower than at the start of the mission in November 1997. They have since recovered by a factor of 1.3. A number of significant solar particle events are indicated. Unfortunately, a significant event occurring on November 9, 2000, was missed due to loss of data transmission.

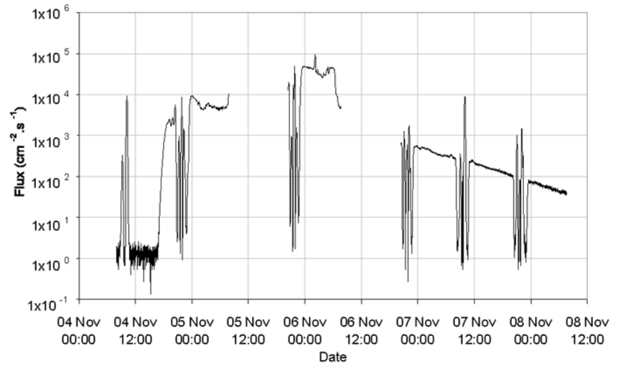

Fig. 3. Time variations of proton fluxes for $E > 38$ MeV for the Guy Fawkes Day Event. Orbits 2928 and 2930 were missing. For most of each orbit, MPTB is fully exposed geomagnetically to solar particles, but on either side of perigee, there is geomagnetic screening and exposure to inner belt protons.

B. Solar Particle Events

1) The Guy Fawkes Day Event: In Fig. 2, it can be seen that the event of November 5–6, 2001, has nearly identical intensity to that of July 14–15, 2000. The time profile of the November 5 event is given in Fig. 3. Unfortunately, two orbits of data were lost, one on November 5 and one on November 6, and these are shown as gaps in the data. The considerable structure seen every 12 h is due to the trapped protons observed on either side of perigee and the geomagnetic screening of solar particles in the same region. For the rest of the orbit, there is almost total exposure to cosmic rays and solar particle events [6], [7]. The integral LET spectra for various orbits during this event are compared with the CREME96 worst-day spectrum in Fig. 4. The CREME96 predictions used throughout this paper correspond to 6 mm of aluminum shielding, equivalent to that covering the CREDO-3 detector. The low LET part of the spectrum (up to about 400 MeV-cm^2 g^{-1}) is dominated by protons, while the higher LET portion is dominated by heavy ions. It can be seen that for the worst orbit (2929), the measurement is close to the CREME96 model.

2) The Bastille Day Event: Time profiles and a preliminary analysis of the event of July 14, 2000, have been given in [7] but

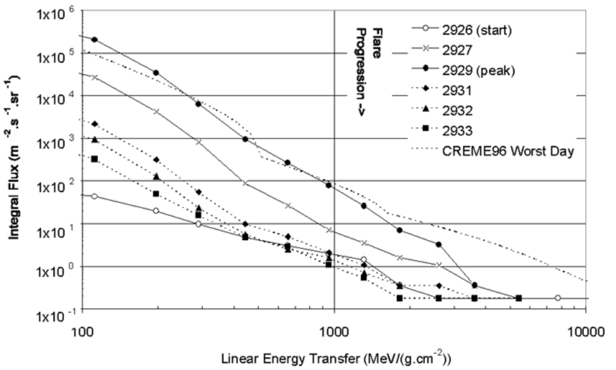

Fig. 4. Integral LET spectra for the fully exposed portion of each orbit during the Guy Fawkes Day Event compared with the CREME96 worst-day model.

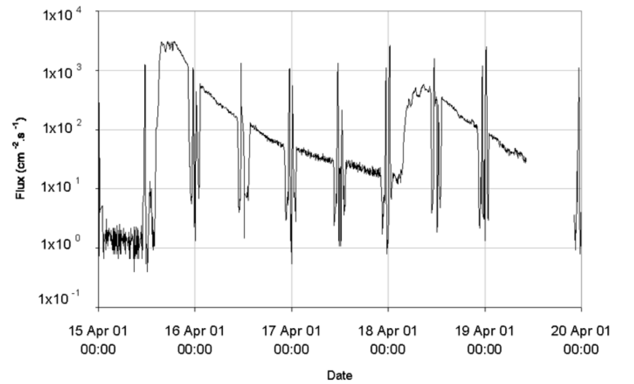

Fig. 7. Time profile of proton fluxes for $E > 38$ MeV as measured by CREDO during the events of April 15 and 18, 2001.

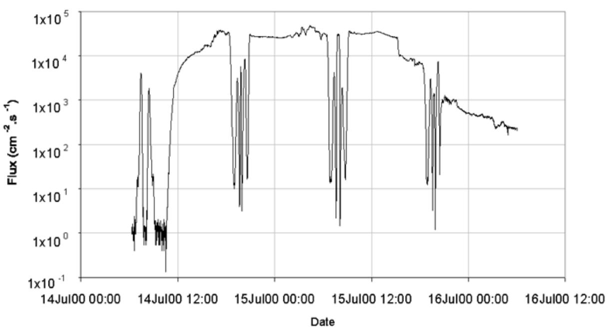

Fig. 5. Time profile of proton fluxes >38 MeV as measured by CREDO during the Bastille Day Event.

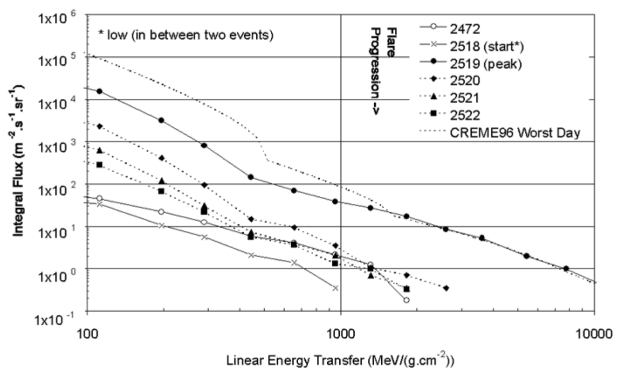

Fig. 8. As for Figs. 4 and 6 but for event of April 15, 2001. This event had significantly fewer protons but equals the worst case for heavy ions.

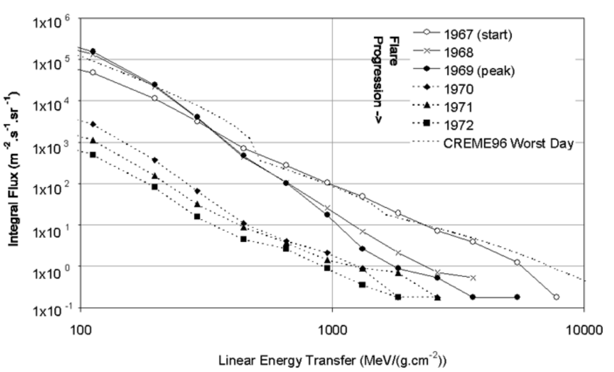

Fig. 6. Integral LET for the fully exposed portion of each orbit during the Bastille Day Event. Here there are two worst-case orbits for protons preceded by a worst-case orbit for ions.

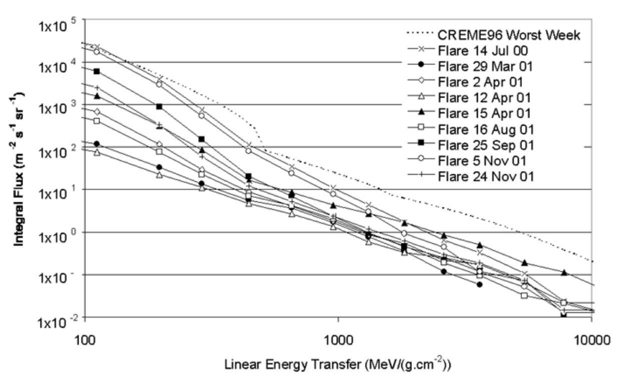

Fig. 9. Integral LET spectra averaged over weeks containing the major solar particle events observed since July 2000 are compared with the CREME96 worst-week model.

for ease of comparison, an extended time profile of the measured proton fluxes is given in Fig. 5.

Fig. 6 gives previously unpublished data for the integral LET spectra on an orbit basis. This event shows changing composition throughout the event with the worst-case day for ions (high LET) preceding the worst-case day for protons (low LET). Both protons and ions approach or exceed the CREME96 model, although at different times.

3) The Event of April 15, 2001: The time profile of this event and the ensuing event of April 18 is given in Fig. 7, while the integral LET spectra for the event of April 15, 2001, are plotted on an orbit basis in Fig. 8. Here the worst orbit shows high LET heavy ions comparable to the CREME96 worst day but shows a significantly lower proton component. Interestingly, this is the strongest ground-level event of the current solar maximum, indicative of a hard proton spectrum. High-energy protons with energies greater than about 300 MeV are required to produce increases in ground-level neutron monitors, even at very low cutoff rigidity. This event was observed at cutoff rigidities of several GV so that the spectrum must extend to GeV energies.

4) Comparison of All Events Since July 2000: In Fig. 9, the worst-case weeks for all events observed since July 2000 are compared with the CREME96 worst week. The latter was a superposition of several events in succession and remains a worst

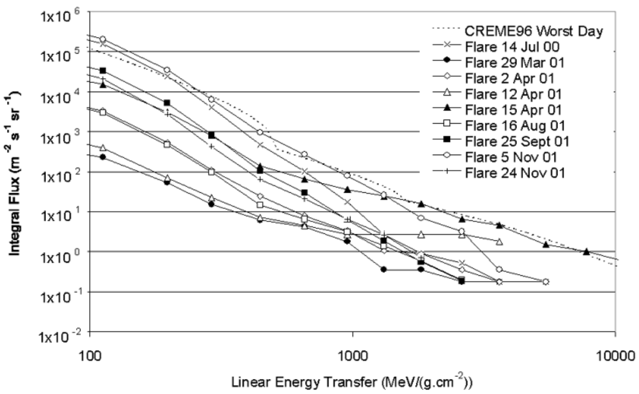

Fig. 10. Integral LET spectra averaged over the worst days of the major solar particle events are compared with the Creme96 worst-day model.

TABLE I
MEASURED PROTON FLUENCES >38 MeV OF CREME96 MODEL

Event/ Model	Worst Day Fluence cm^{-2}	Worst Week Fluence cm^{-2}
CREME 96	1.48×10^9	2.66×10^9
14-20 July 2000	2.53×10^9	2.80×10^9
15-21 April 2001	1.03×10^8	1.33×10^8
5-11 Nov 2001	1.7 to 3.4×10^9	2.0 to 3.7×10^9

case when compared with the events of this cycle, which typically lasted no more than 3 d. The three events that approach the worst-case model are those discussed in more detail above: July 14, 2000, April 15, 2001, and November 5, 2001. Again, it can be seen that the event of April 15, 2001, has a strong ion component but fewer protons compared with other events. Based on GOES data, the event of November 9, 2000, may well have been comparable, but data from MPTB were not obtained.

In Fig. 10, the worst-day averages are compared with the CREME96 worst-day model. The heavy-ion component in the model is equaled by the level during the event of April 15, 2001, although the level of protons during this event is well below the model. The events of July 14, 2000, and November 5, 2001, have a significant heavy-ion component but do not reach the model levels. The plots are terminated at 10^4 MeV/(g cm^{-2}), as statistics during individual events are poor above this value of LET. In fact, each of the three events gave one count in the channel greater than 11 800 MeV/(g-cm^{-2}). For the longer accumulation times available for cosmic rays, significant counts are obtained in both this and the highest channel [>19 800 MeV/(g-cm^{-2})]. The presence of very high LET ions is of significance in both solar particle events and quiet time.

Both the events of July 14, 2000, and of November 5, 2001, appear to exceed the spectrum at low LET, indicating that the proton levels may be greater than in CREME96. This has been investigated further using data from the proton channel, and comparisons are made in Table I.

Uncertainties in the fluences for the November 5, 2001, event arise from missing orbits in the data set. However, proton fluxes during both this and the July 14, 2000, event seem to exceed the worst-day model in CREME96. It is interesting to compare

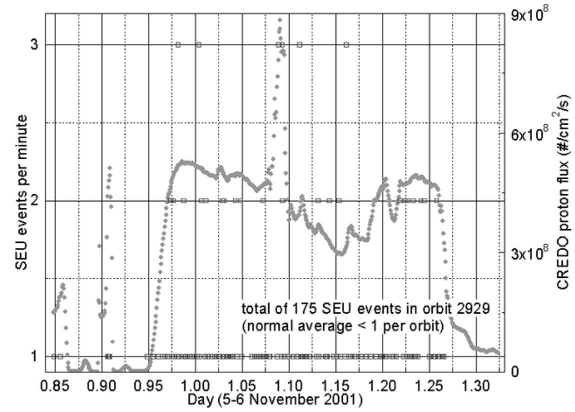

Fig. 11. Single-event effects (shown as squares) observed in the ADC experiment on MPTB are compared with proton fluxes for $E > 38$ MeV (shown as triangles) measured by CREDO-3 during the worst orbit of the Guy Fawkes Day event. A total of 175 upsets were observed in three devices.

these fluences with the trapped proton fluence of 1.02×10^{10} cm^{-2} accumulated over the two years from July 2000 to July 2002. For this orbit during this solar maximum, the contributions of solar particles and trapped protons are nearly identical.

C. Single-Event Effects in ADCs

Single-event effects have been observed in the MPTB experiments during these events, and Fig. 11 shows upsets observed in the ADC experiment [9] together with proton fluxes measured by CREDO during the worst orbit (2929) of the November 5, 2001, event. The average rate before and after the event is about 0.29 upsets per device day, while the average rate over the worst orbit is 117 upsets per device day.

An identical copy of the board has been subjected to ground testing by ions and protons under operating and input conditions identical to those employed in the space test [9]. Based on measured cross-sections, the cosmic-ray contribution is only 0.1 upset per device day. Most of the quiet-time upsets come from radiation belt protons. measured cross-sections and the CREDO measurements of the LET spectrum. For protons, measurements were obtained at only two energies, 63 and 200 MeV, and the device upset cross-sections were found to be essentially flat with energy at 1.8×10^{-8} and 2.0×10^{-8} cm^2, respectively. Given the lack of data, first-order estimates of trapped proton and solar proton upsets have been obtained by simply multiplying the integral fluences greater than 38 MeV by the plateau cross-section of 2×10^{-8} cm^2. Shielding has a significant influence on upset rates, particularly for the softer spectra associated with solar particle events. MPTB was designed so that all test boards, including CREDO, had similar shielding with 1.4 mm of aluminum on the space side and a large amount of shielding (30 g-cm^{-2}) on the spacecraft side. Hence measurements taken by CREDO are reasonably representative of the environment at the ADC devices. However, uncertainties due to circuit boards, lids, etc., could give factor of two uncertainties in the solar particle estimates. The results are compared with observations in Table II. Good agreement is obtained. For this event, it can be seen that ions and protons make comparable contributions.

TABLE II
CALCULATED UPSET RATES USING CREDO MEASUREMENTS COMPARED WITH OBSERVATIONS

SEU per device-day	Quiet-Time	Orbit 2929
Observed	0.29	117
Calculated for cosmic rays	0.1	0.1
Calculated for trapped protons	0.2	0.2
Calculated for solar ions	0.0	41
Calculated for solar protons	0.0	70

IV. CONCLUSION

The results of the analysis of our observations of solar particle events during the maximum of solar cycle 23 can be summarized as follows.

1) Three events show worst-day LET spectra that are very close to and possibly exceed the CREME96 worst-day model.
2) For two events (July 14, 2000, and November 15, 2001), the proton fluxes and heavy-ion component are both comparable to the worst-day model, although not necessarily at the same time (July 14, 2000).
3) For the event of April 15, 2001, the heavy-ion component equals the worst-day model but the proton component is significantly less.
4) For the events of July 14, 2000, and November 5, 2001, the worst-day proton fluences slightly exceed the model.

Our observations of the events of July 14, 2000, and November 5, 2001, are consistent with the models of Xapsos *et al.* [10]–[12], which indicate that the CREME96 worst-day proton model is in fact a 90% worst case rather than a 99% worst case. In designing for worst-day SEE rates, it would be advisable to use the model of Xapsos *et al.* for proton rates in conjunction with the CREME96 model for heavy-ion rates. Also, the CREME96 worst-week proton fluence is very close to the observations, while the integral LET spectrum still exceeds all the measured events. The CREME96 worst week comprises several events in succession.

The extreme variability of solar particle events implies that SEE rates can be interpreted only in the light of measured proton fluxes and ion LET spectra, the relative importance of which can vary even within an event. Good agreement has been obtained between observations and predictions based on such measured fluxes for the ADC experiment on MPTB during the event of November 5, 2001. It would be extremely valuable to perform further comparisons for the other large events using device upset data from both this and other spacecraft.

Some devices are susceptible only to ions, and it is important to know which SPEs contain a significant fraction. For example, the measured heavy-ion enhancement during November 5, 2001, has proven essential to the interpretation of a major anomaly on the NASA Microwave Anisotropy Probe [4]. Here the anomaly was diagnosed as a single-event transient and the device is susceptible to ions but has no proton sensitivity. In designing warning monitors for spacecraft, it must be recognized that both components should be measured.

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