Observation of the Solar Particle Events of October and November 2003 From CREDO and MPTB

Clive S. Dyer, Karen Hunter, Simon Clucas, and A. Campbell

***Abstract*—Proton fluxes, linear energy transfer spectra, and single-event effects (SEEs) rates for the five solar particle events occurring during October 26 to November 6, 2003, are compared with previous events of the current solar maximum and with environment models. It is shown that this period includes the worst week for the current solar maximum and that this exceeds the October 1989 worst week in protons but not in ions. The SEE rates illustrate the importance of allowing for both proton and heavy ion contributions, the relative importance of which varies from event to event and with time during individual events.**

***Index Terms*—Dynamic random access memories (DRAMs), heavy ions, linear energy transfer spectra, protons, single-event effects (SEE), solar particle events.**

I. Introduction

SOLAR PARTICLE EVENTS (SPEs) can lead to greatly enhanced single-event effects (SEEs) rates in space systems, sometimes resulting in serious anomalies and losses. Both direct ionization by heavy ions and the nuclear reactions of protons contribute to the rates in varying degrees depending on the susceptibility of the technology and the spectra and composition of the particular event. In order to assure radiation hardness of space systems, it is important to design to a sensible worst-case event and this is currently embodied in the CREME96 model [1], which is based on the events of October 19–27, 1989.

During the current solar maximum several large SPEs have been observed which approach or exceed the CREME96 worst day. The Microelectronics and Photonics Test Bed (MPTB) carries a number of test boards of electronics together with the CREDO-3 monitor to record proton fluxes and the linear energy transfer (LET) spectra of ions. Previous literature has presented a description of the CREDO instrument [2] and data on the events up until July 2002, including the Bastille Day event of July 14, 2000 [2] and the Guy Fawkes Day event of November 5, 2001 [3]. These data have been used to interpret single-event upset (SEU) rates in dynamic random access memories (DRAMs) [4] and single-event transient (SET) rates in analog-to-digital converters [3]. The Guy Fawkes Day event led to a serious anomaly in the Microwave Anisotropy Probe (MAP) spacecraft as a result of what appears to be a SET in a PM139 voltage comparator [5].

This paper extends the MPTB–CREDO data to June 2004 and compares the Halloween events of October and November 2003 with the previous events of the solar maximum and with the CREME96 models. The extended activity enables comparisons to be made with the worst week as well as worst-day specifications. Correlations are also made with MPTB experiments and other available SEE data.

II. The Halloween Events

Just when it was thought that the solar maximum was all over, the Sun provided 15 days of extraordinary activity during October and November 2003, termed the *Halloween Storms* by the Space Environment Center [6]. Between October 19 and November 5, three active regions produced 17 major flares, three of which exceeded the Bastille Day event in X-ray intensity and one of which (November 4) is probably the largest X-ray event on record. Six distinct solar particle increases were observed by GOES. The coronal mass ejections from the events of October 28 and 29 were amongst the fastest on record, arriving at earth after only 19 hours and producing the most intense geomagnetic storms of the current solar cycle.

A review of the related spacecraft and ground anomalies has been given in [7]. Ground-induced currents led to power outages in Sweden, while communications problems and radiation alerts led to rerouting of many aircraft to lower altitudes and latitudes. Ground-level neutron monitor increases were experienced on October 28 and 29 and on November 2. A 40% increase in radiation levels was observed at 39 000 feet on a flight from LAX to JFK on October 29 [8]. Analyses of atmospheric radiation and solar particle enhancements are the subject of other papers [9], [10].

Problems occurred on at least 28 spacecraft [7], with effects such as star tracker saturation, instrument switch-off and CPU resets. Many spacecraft were intentionally put into safe mode, including five NASA earth observation spacecraft on which all instruments were switched off. A very large number of recoverable SEUs and SETs have been recorded and some have been subjected to initial analysis [11].

III. 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 MPTB [4], [12], which is

Manuscript received July 20, 2004; revised September 2, 2004. The work at QinetiQ was supported by the U.K. Ministry of Defence, while the work at the Naval Research Laboratory was supported in part by the U.S. Defense Threat Reduction Agency.

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Digital Object Identifier 10.1109/TNS.2004.839156

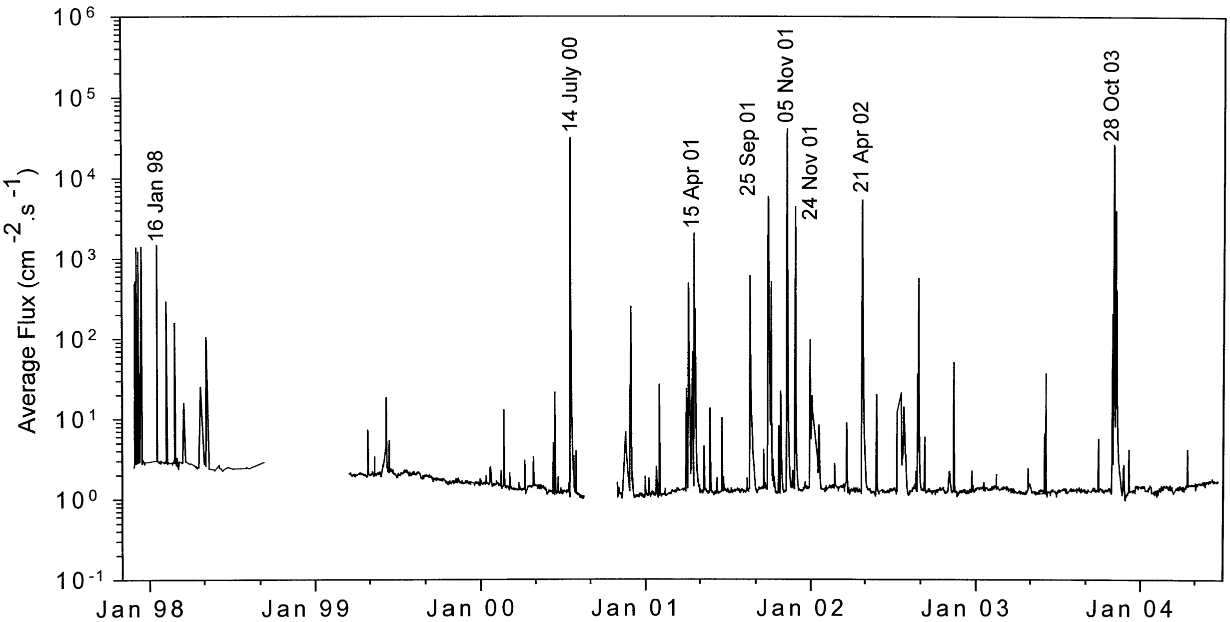

Fig. 1. Proton flux measurements from CREDO-3 on MPTB between November 1997 and June 2004 show the underlying cosmic-ray modulation with a minimum intensity in August 2000, together with a number of very significant SPEs, seen as spikes, including the Halloween events of 2003.

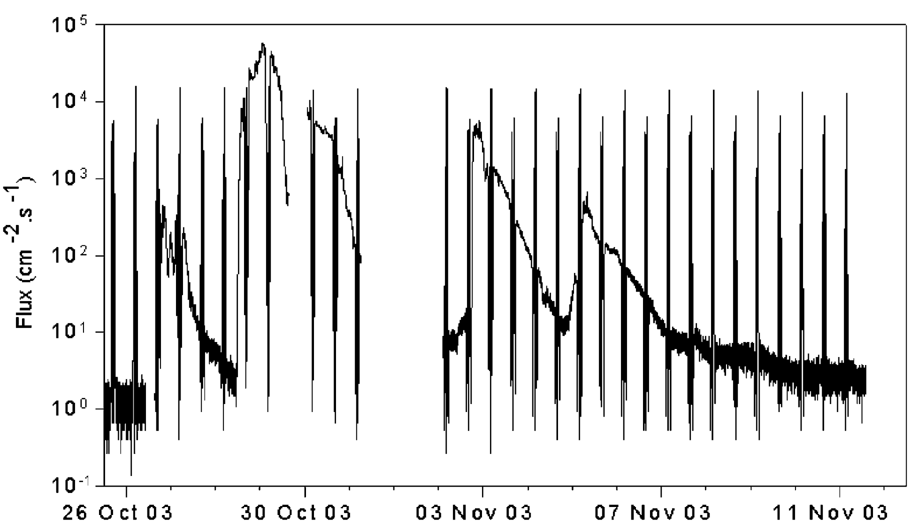

Fig. 2. Time variations of proton fluxes for the Halloween events. There are three orbits of missing data. For most of each orbit MPTB is fully exposed geomagnetically to solar particles but on either side of perigee there is geomagnetic screening, leading to the lowest levels and exposure to inner-belt protons, seen as spikes in the data.

aimed at space testing a number of advanced technologies in a radiation-stressing, highly inclined (63^0) elliptic orbit ($39\,200 \times 1200$ km) having a period of 12 hours. Results from CREDO up until July 2002, together with an instrument description, have been presented in [2] and [3] while results on SEE are given in [3] and [4].

The proton telescope measures fluxes of protons of energy greater than 38 MeV, while the ion monitor measures 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 the present (July 2004) with the exception of a few periods of eclipses at around perigee and other minor data outages.

IV. Results

A. Time Variations of Proton Fluxes

The time variation in the proton fluxes is shown in Fig. 1 for the period from November 1997 to June 2004. The underlying, slowly varying level is from cosmic rays for which flux levels reached a minimum in August 2000 when they were a factor 2.7 lower than at the start of the mission. They have since recovered by a factor 1.5. The significant SPEs are seen as spikes lasting for several days each. Dates are given for the most significant increases, including the Halloween events. It can be seen that the event of October 28–29, 2003, is comparable to the largest of the previous events of this solar maximum. Unfortunately the large SPE on November 9, 2000, was missed.

The time profile of the Halloween events is given in Fig. 2. Unfortunately three orbits of data were lost, one on October 29

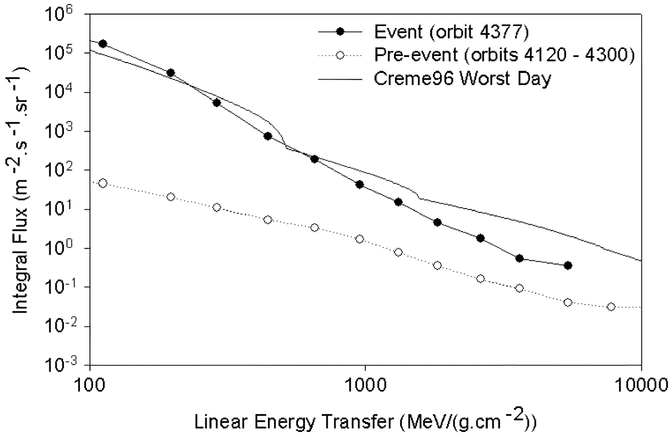

Fig. 3. Integral LET spectrum under 6 mm of equivalent aluminum shielding for the fully exposed portion of orbit 4377 during the peak of the October 28 event, compared with the pre-event spectrum and the CREME96 worst-day model.

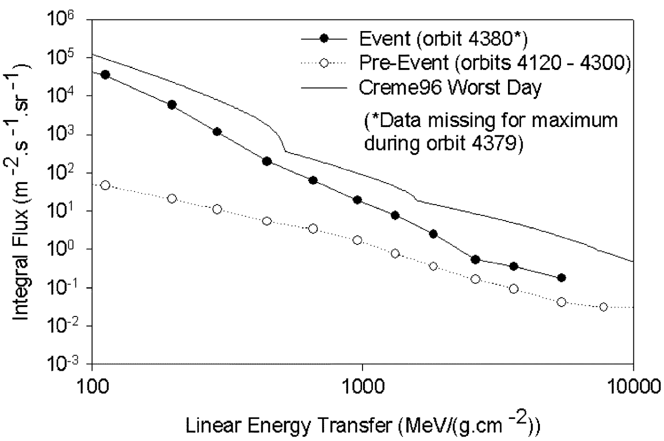

Fig. 4. Integral LET spectrum under 6 mm of equivalent aluminum shielding for orbit 4380 on October 30, 2003.

and two on November 1. Five distinct solar particle increases are discernible at this energy (>38 MeV) with start dates of October 26, October 28, October 29, November 2, and November 4. The largest event is that of October 28, while the event of November 4 is significantly less intense in protons although it is the most intense in X-rays. This could in part be due to its location on the western limb of the Sun where connection to the Earth via the interplanetary magnetic field is less favorable compared with optimum heliolongitudes around 40° to 50° west. The considerable structure seen every 12 hours is due to the trapped protons seen as spikes in the data on either side of perigee and the geomagnetic screening of solar particles in the same region, leading to the lowest levels. For the rest of the orbit there is almost total exposure to cosmic rays and SPEs [2].

B. Integral LET Spectra

The integral LET spectra for various orbits during these events are compared with the CREME96 worst-day spectrum in Figs. 3–6. The first gives the peak spectrum on October 28–29 (1520 to 0234 UT), while the second gives the spectrum for October 30 (0233-1506 UT) during the decay phase of the October 29 SPE. Unfortunately the orbit (4379) during the

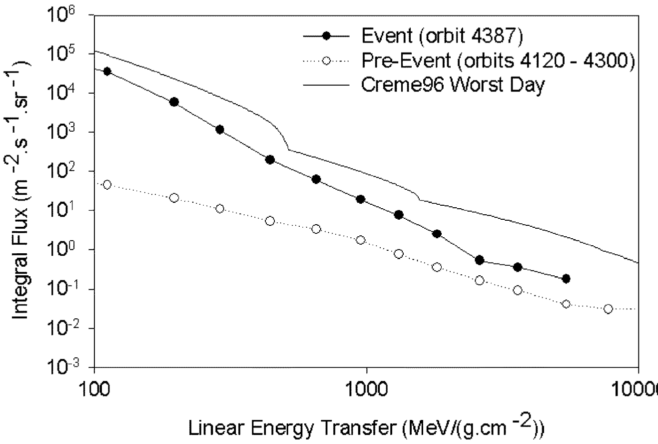

Fig. 5. Integral LET spectrum under 6 mm of equivalent aluminum shielding for orbit 4387 during the November 2 event.

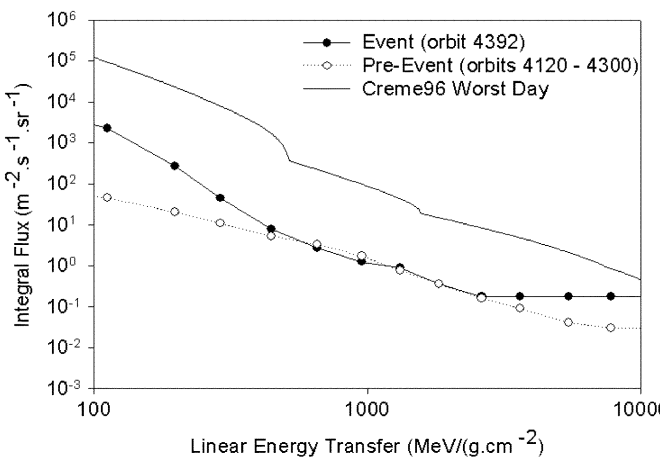

Fig. 6. Integral LET spectrum under 6 mm of equivalent aluminum shielding for orbit 4392 during the November 4–5 event.

peak of this event suffered data loss. Fig. 5 gives the spectrum for the peak of the November 2 event (1455–0211 UT), while Fig. 6 gives the peak of the November 4 event (0204–1438 UT on November 5). Note that in the last case the statistics of the high LET increase are extremely poor and the apparent upturn is not considered real. The CREME96 worst-day predictions used throughout correspond to 6 mm of aluminum shielding, equivalent to that covering the CREDO-3 detector. The October 28, 2003, event is very comparable to the CREME96 worst day, slightly exceeding it at low LET, while the succeeding events are progressively lower. Unfortunately the peak of the October 29 event was not measured.

C. Comparison With Other Events and Models

In Fig. 7 the integral LET spectrum for the event of October 28, 2003, is compared with the events of July 14, 2000, April 15, 2001, and November 5, 2001. Three of the events exceed CREME96 at low LET where protons dominate. Note that the orbit given for the July 14, 2000, event is that for the peak proton flux (orbit 1968) and that for this event the ions peaked earlier (orbit 1967) at which time they matched the CREME96 high LET spectrum [3]. The events of October 28, 2003, and

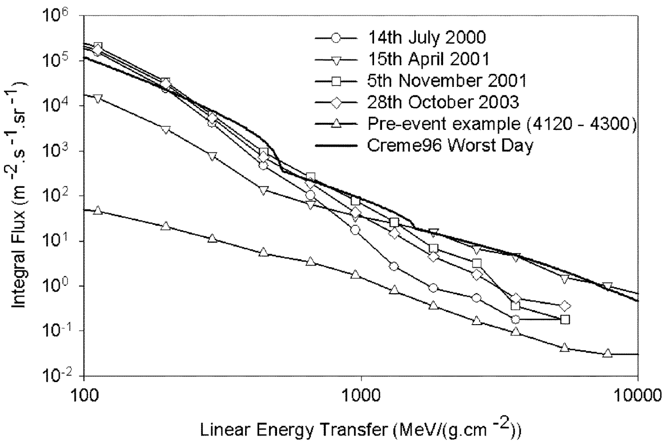

Fig. 7. Integral LET spectrum under 6 mm of equivalent aluminum shielding at the peak of the October 28, 2003, event is compared with the previous largest events of this solar maximum and with the CREME96 worst day.

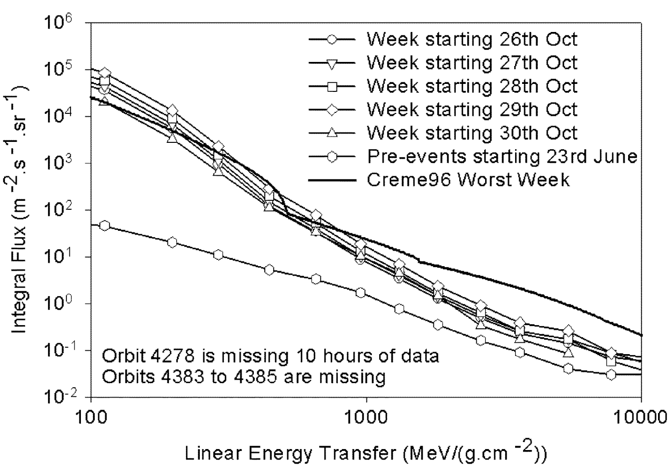

Fig. 8. One-week rolling averages during the period October 26, 2003, to November 6, 2003, are compared with the CREME96 worst-week model.

November 5, 2001, have significant heavy ions but are somewhat below CREME96, while the April 15, 2001, event is the most intense in heavy ions despite being significantly less intense in protons.

The occurrence of several successive events over the course of a week or so during the Halloween events is a very comparable situation to that of October 19–27, 1989, which was used to create the CREME96 worst-week specification. Spectra from worst weeks around the previous events of this solar maximum have all fallen below the CREME96 worst week as they have been isolated events [3].

In Fig. 8 the one-week averages for various starting dates during the Halloween events are compared with the CREME96 worst week. These have some missing data and are hence lower limits. The CREME96 worst week is significantly exceeded at low LET but exceeds the latest events at high LET. The low LET result has been checked using the proton monitor with interpolation over missing orbits and the fluences over the major events of this solar maximum are presented in Table I. The worst-week fluence for the Halloween week is 3.33×10^9 cm^{-2} compared with 2.66×10^9 cm^{-2} for CREME96. The week of November 5–11 is higher but this is highly dependent on interpolated data.

TABLE I
MEASURED PROTON FLUENCES >38 MeV cf. CREME96 MODEL

Event/Model	Worst Day Fluence cm^{-2}	Worst Week Fluence cm^{-2}
CREME96	1.48×10^9	2.66×10^9
14-20 July 00	2.53×10^9	2.80×10^9
15-21 April 01	1.03×10^8	1.33×10^8
5-11 Nov 01	2.77×10^9	3.94×10^9
28 Oct-3 Nov 03	2.22×10^9	3.33×10^9

The total measured solar proton fluence greater than 38 MeV for this solar maximum based on 6.6 years of CREDO data is 1.3×10^{10} cm^{-2}. This does not include the event of November 9, 2000, which could have added about 2.3×10^9 cm^{-2} based on GOES data. It is interesting to note that this total is very comparable with the fluence of 1.7×10^{10} cm^{-2} obtained from the JPL-91 model [13] for seven years at solar maximum at the 90% confidence level, calling into question whether this is sufficiently conservative. The Emission of Solar Protons (ESP) model [14] gives a fluence of 2.1×10^{10} cm^{-2} for the same conditions.

It is also of interest to compare the results of Table I with the ESP worst-case event model. For the 90% confidence level this gives worst-case event fluences above 40 MeV of 2.9×10^9 cm^{-2} for a one-year mission and 7.9×10^9 cm^{-2} for a seven-year mission. It should be borne in mind that an event lasts more than one day (typically two) and so the CREME96 model is consistent with the one-year 90% ESP case. It is also worth noting that the anomalously large event used in the King model and based on the event of August 1972 gives an event fluence of 5.6×10^9 cm^{-2}. The MPTB/CREDO-3 data taken over nearly seven years are consistent with the ESP model and suggest that this model should be employed for proton-induced SEE using the confidence level desired by the project.

D. Correlation With Effects

SEEs have been observed in the MPTB experiments during these events and Fig. 9 shows the total upset rates observed during the period September 20 to November 5, 2003, in four 16-Mbit NEC DRAMs on board B6 of MPTB. The devices used are those facing into the spacecraft as those facing out are experiencing too much leakage current due to the accumulated dose. The large increase in upset rates during the events of October 28 and 29 can be readily seen. In Table II the upset rates are compared with those during previous events and CREDO measurements of proton fluences >38 MeV and ion fluences of LET >1.82 MeV/(mg cm^{-2}). The results are plotted as histograms in Fig. 10. All rates and fluences are per device and per orbit (i.e., 12 hours). The average upset rate for the peak day of the October 28–29 events is 179 per device-day compared with a quiet-time rate of 3.1 per device day from galactic cosmic rays and inner-belt protons. This may be compared with a peak day rate of 225 per device-day during the Bastille Day event. A previous detailed analysis of SEU rates during the Bastille Day event showed that in the light of CREDO measurements and measured proton and ion cross-sections, the ratio of ion-induced to proton-induced upsets was about 2:1 [7]. Note that during the October 2003 events the fluxes of both protons and heavy

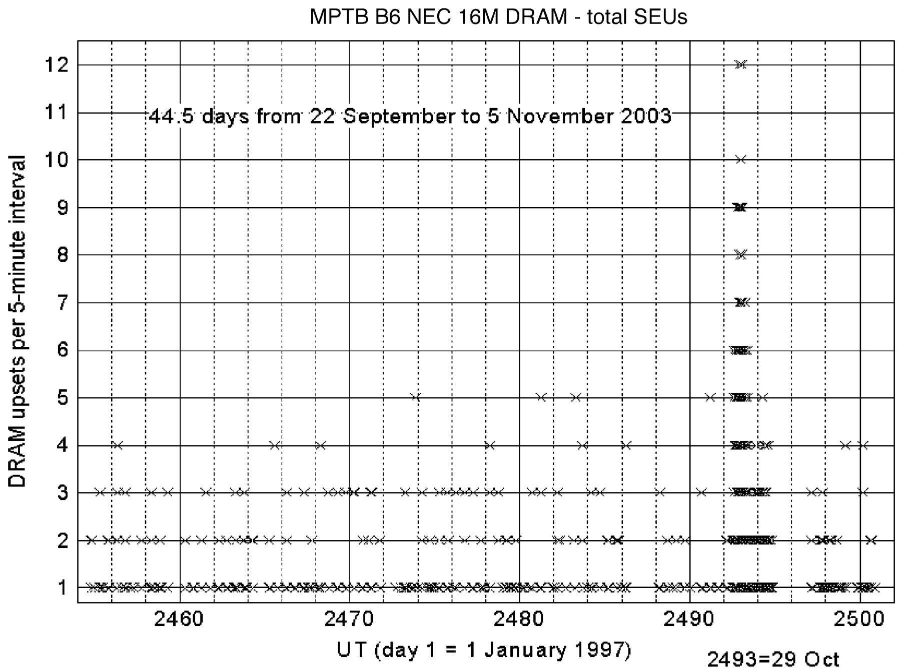

Fig. 9. Upset rates in four 16-Mbit DRAMs on MPTB for the time period September 22 to November 5, 2003, showing the increases from the Halloween events.

TABLE II
UPSET RATES IN DRAMS FOR MAJOR SPEs cf. CREDO PROTON AND ION FLUENCES

Orbit No	Day/ Time	Proton Fluence (10^9 cm^{-2}	Ion Fluence (cm^{-2})	SEU per device
1967	14 Jul 00 0619-1822	0.24	587	125
1968	14-15 Jul 00 1824-0611	1.2	127	100
2519	15 Apr 01 1032-2216	0.1	451	29
2927	4-5 Nov 01 1950-0750	0.26	67.6	21
2929	5-6 Nov 01 1946-0746	1.8	262	146
4377	28-29 Oct 03 1520-0234	1.1	231	131
4378	29 Oct 03 0311-1511	1.1	119	48
4380	30 Oct 03 0233-1506	0.20	104	30
4387	02-03 Nov 03 1455-0211	0.17	43	12

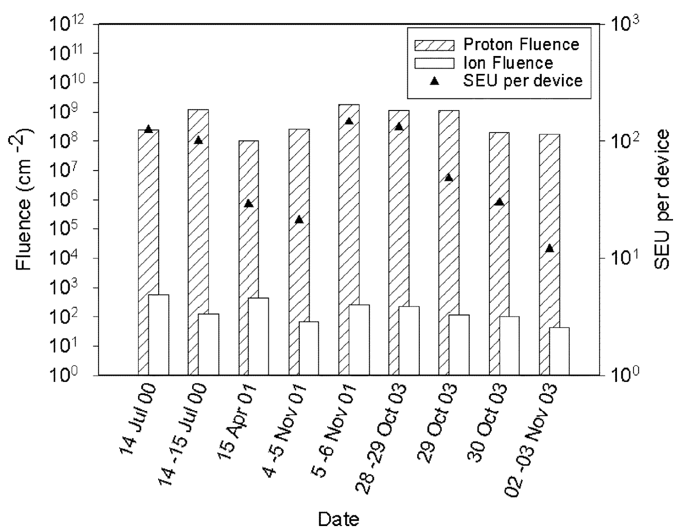

Fig. 10. Proton and ion fluences per 12-hour orbit from CREDO-3 on MPTB compared with SEUs per 16-Mbit DRAM.

ions were simultaneously elevated, whereas during the Bastille Day event the peaks occurred at different times. The SEU rates during the events of November 2 and 4, 2003, are relatively low.

These data show the worst orbit for SEU to be 2929 on November 5–6, 2001, when both protons and ions were simultaneously high. Comparison of orbits 1968 (July 14–15, 2000) and 4378 (October 29, 2003) shows that particle fluxes were comparable but that SEU rates were different by a factor two. Other factors such as spectral hardness are probably responsible.

SEU data from the solid state recorder (SSR) carried on the Orbview-2 mission have been analyzed in [15] in which upsets during the major SPEs occurring between July 14, 2000, and April 21, 2002, were compared with proton fluxes measured by GOES. The SSR comprised 512 Mbit of memory provided by 4-Mbit MOSAIC/HITACHI DRAMs (MDM1400G-120) and protected by Hamming Error Detection and Correction Code. The orbit was a circular 750 km altitude, 98° inclination, and sun-synchronous for which the high latitude portions of each orbit are vulnerable to SPEs. Additional data up until November 2003 have recently been provided [11]. These extended data have now been compared with proton and ion fluences from CREDO-3 on MPTB and the results are presented in Fig. 11. The LET threshold for ions is again 1.82 MeV/(mg cm^{-2}) and this corresponds well with the threshold reported in [15]. It can be seen that the correlation with particle fluences is again complex and that both ions and protons are contributing

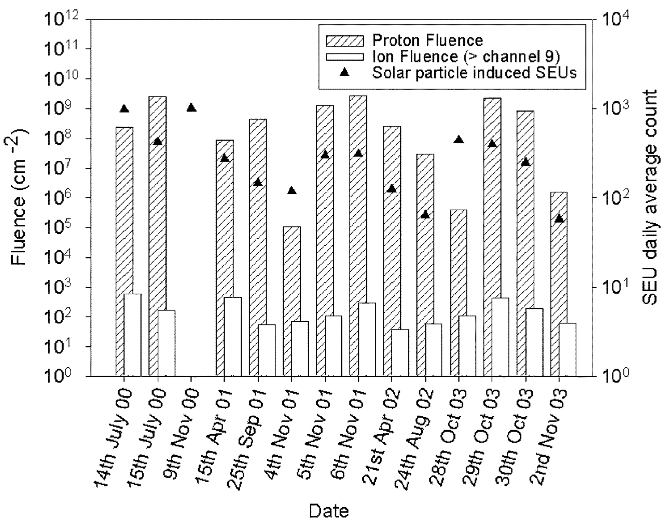

Fig. 11. Proton and ion fluences per day from CREDO-3 on MPTB are compared with SEU data from the Orbview-2 SSR.

in varying degrees from event to event. For example, as in the MPTB DRAMs, the SEU rate drops between July 14 and 15, 2000, while the proton flux increases. This is probably due to the decreasing ion flux that was noted above, although changes in proton spectra could also be a contributory factor.

V. Conclusion

For the current solar maximum there are now four events which have shown worst-day LET spectra that are very close to and possibly exceed the CREME96 worst-day model. For three events (July 14, 2000, November 5, 2001, and October 28, 2003) the proton fluxes and heavy-ion component are both comparable to the model, although not necessarily at the same time (for example the July 14, 2000, event showed ion fluxes peaking before proton fluxes). For the event of April 15, 2001, only the heavy-ion component is comparable with CREME96.

The CREME96 worst week has been exceeded in protons by the worst Halloween week as well as possibly the worst weeks of July 2000 and November 2001. However, it remains worst case in heavy ions.

The worst-event and mission-integrated fluences of protons are consistent with the ESP [14] model and it may be preferable to use this to assess proton-induced upsets.

The extreme variability of these 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. Additional factors, such as particle spectra and device shielding, must also be taken into account.

Some devices are susceptible only to ions and it is important to know which SPEs contain a significant fraction of ions. Interestingly the MAP SET anomaly did not reoccur during the Halloween events despite the high LET spectrum being comparable to the November 5, 2001, event. As probabilities during a worst day are calculated to be about 0.5 per day this is probably due to the limited statistics [11].

Acknowledgment

The authors would like to thank C. Poivey, J. Barth, and K. LaBel of NASA/Goddard Space Flight Center for information concerning MAP and the Orbview-2 data. The solar proton fluences from the JPL-91, King, and ESP models were obtained using the SPENVIS website (spenvis@oma.be).

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