A Space Weather Event on the Microwave Anisotropy Probe (MAP)

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***Abstract*--NASA's Microwave Anisotropy Probe (MAP), at the L2 libration point, experienced a reset of the spacecraft's processor on November 5, 2001. We have concluded that the cause was increased levels of radiation from the 4 November solar storm.**

I. Introduction

NASA's Microwave Anisotropy Probe (MAP) was launched on 30 June 2001. After three months of phasing loop operations, the MAP reached its final position at the L2 libration point where it operated normally for about one month. On November 5, 2001 a reset of the spacecraft's processor was observed, and the spacecraft entered a "safehold" condition. The spacecraft was returned to normal operations. Because a large solar storm occurred on November 4, 2001 it was suspected that increased levels of radiation caused the reset. NASA began an investigation of the anomaly, which focused on the power on reset (POR) circuitry of the processor. The investigation team also sought information on the space environment at the time of the anomaly.

II. Radiation environment at L2 during the anomaly

The L2 position is approximately 1.5 million kilometers from Earth in the anti solar direction. To maintain its orbital position, MAP makes large "halo" orbits around the L2 point. Normally, the high-energy radiation environment at L2 consists of galactic cosmic ray (GCR) ions, which are composed of all elements of the periodic table in a broad energy spectrum. The GCR ions are present at all times at low levels. Some solar events can produce particles that cause the ion levels to increase suddenly by orders of magnitude. The ions can be accelerated at the site of a solar flare or in the shock wave of a coronal mass ejection (CME). As the solar event particles are transported by the solar wind, they diffuse throughout interplanetary space so the particle flux depends on the distance from the sun. In astronomical units (AUs), the L2 position is very close to the Earth at 1 AU, therefore, the high-energy (> 10 MeV) particle levels at L2 are approximately the same at those observed near the Earth at geostationary.

The frequency and intensity of solar storms depends on the 11-year solar activity cycle. The sun is now in the active phase of the cycle; therefore, an increased number of solar storms with subsequent increases in the number of solar particle events have been observed. On November 4, 2001 at 16:35 UT a partial CME halo was observed and by 16:50 UT the CME was a full halo and an X1.0 class solar flare was observed. A proton storm followed as measured by the GOES 8 spacecraft. Fig. 1 shows the GOES measurements for November 4-6, 2001. Note the 2-3 orders of magnitude increase in the > 100 MeV protons on November 4. For high-energy particles, the GOES measurements can be used to approximate the proton levels at the location of MAP.

It is also important to have measurements of the heavier ions during solar particle events when resolving anomalies on spacecraft. Some heavy ion measurements are available from the ACE and SOHO spacecraft (He only); however, they do not have adequate energy and elemental coverage for engineering applications. The CREDO3 instrument [1] flying on the Microelectronics and Photonics Testbed (MPTB) measured the linear energy transfer (LET) spectra during the event as seen in Fig. 2. The LET measurement of the environment is a very useful metric for understanding the level of threat that solar storms pose to microelectronics because it allows a direct comparison to ground test data. The sensitivity of microelectronics single event effects (SEEs) is characterized by expressing the SEE cross section as a function of the LET of the particles used in the test. Figure 2 shows the event average LET spectrum (from orbit #2926, starting around 07:56 UT on November 4, to orbit #2931, finishing around 07:40 UT on November 7), and the worst case orbit LET spectrum (orbit #2929 starting around 19:45 UT on November 5). Unfortunately, the data from orbits #2928 and #2930 are missing. These measured LET spectra are compared to the CREME96 environment model using a "worst day" spectrum behind 6 mm of aluminum shielding as input parameters. The 6 mm of shielding is equivalent to the shielding covering the CREDO3 detector. It can be seen that for the worst orbit (#2929) the measurement is close to the CREME96 worst day model. Note that the CREDO3 detector covers a LET range from 0.1 to 20 MeV-cm^2/mg

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and that the statistics for low fluxes are poor above a LET of 1 MeV-cm^2/mg.

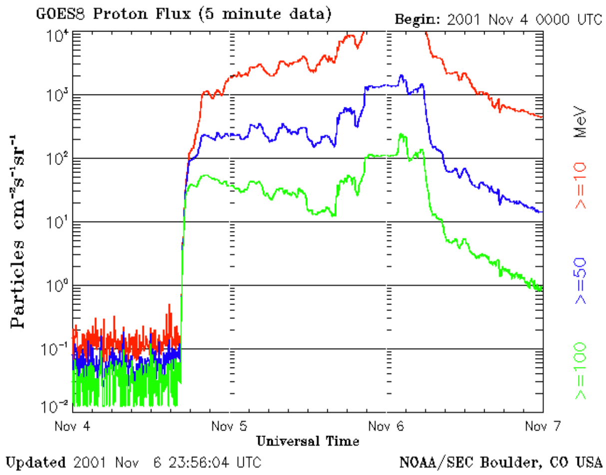

Fig. 1. Solar proton measurements from the GOES 8 spacecraft at geostationary

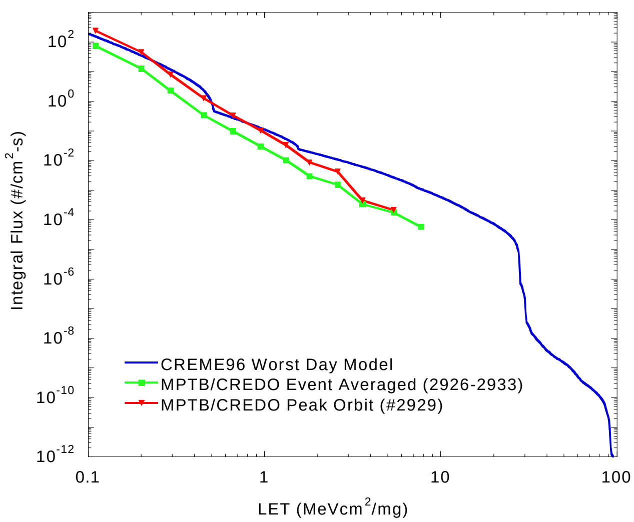

Fig. 2. Integral LET spectra as measured by CREDO3 on MPTB during the Guy Fawke event (November 5-6, 2001), and comparison with the CREME96 worst day model.

III. DESCRIPTION OF THE SET SUSCEPTIBLE CIRCUIT

The POR circuitry of the MAP control and data handling (C&DH) subsystem is shown in Fig. 3. It is made with 54AC14 inverters with Schmitt trigger inputs from National Semiconductors and PM139 voltage comparators from Analog Devices. The 54AC14 FACT technology from National Semiconductors has a very low single event upset (SEU) and single event transient (SET) sensitivity with a worst case LET threshold of 40 MeVcm^2/mg [2]. In addition, with a Schmitt trigger input, this specific function will have a negligible SET sensitivity. The PM139 voltage comparators are known to have a significant SET sensitivity [3, 4, 5,6].

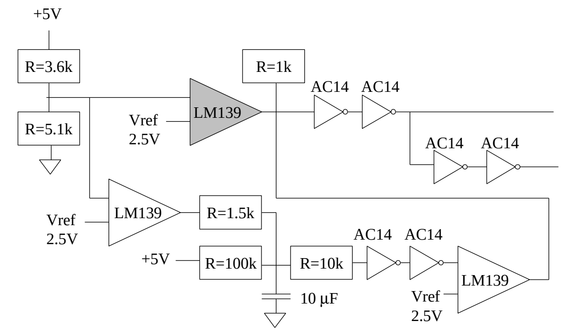

Fig. 3. Reset circuitry

To cause a reset, the SET amplitude needs to be higher than 2.5 V. Typical SET waveforms on 139 devices are shown in Fig. 4. The waveforms all have a similar shape: a very sharp rise time followed by an exponential decay. Maximum transient amplitude is rail to rail. Transient amplitude depends on the bias conditions, the ion LET value, and the ion impact location. For low input differential voltage values (δV_{in} < 0.8 V), about 90% of the transients have a rail to rail amplitude for all LET values [7]. The duration depends on the pull-up resistor value and the output load. For a 1 kohm pull up resistor and a low load capacitance (as used in the MAP reset circuit), typical Full Width at Half Maximum (FWHM) is on the order of 1 microsecond.

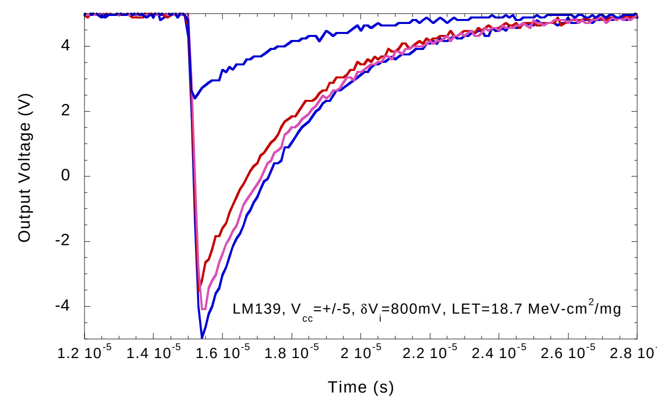

Fig. 4. LM139 transient waveforms.

The SET sensitivity of the PM139 voltage comparator varies with the input differential voltage. The sensitivity is very high for low differential input voltages, and decreases significantly for δVin greater than 0.8 V. For δVin greater than 2 V, the sensitivity is quasi negligible with a LET threshold of about 25 MeV-cm^2/mg. One of the comparators used on MAP POR circuit has a δVin of about 2.5 V; therefore, it is not sensitive to SET. The two others voltage comparators have a 400 mV δVin, so they are sensitive to SET. Only one of these two comparators can induce the reset, because a large capacitor at the output of the other is supposed to filter out the SET.

IV. SET SENSITIVITY OF THE PM139

A. Test data

The PM139 was tested for bias conditions close to the MAP application (+5/0V power supply, 200 mV δVin) [6]. The results obtained were nearly identical to the results of LM139 devices from National Semiconductor for a +/-5V power supply voltage and δVin of 200 to 400 mV [7]. The SET cross section curves are shown in Fig. 4. The low LET threshold (about 4 MeV-cm^2/mg) often is an indicator that the device is also sensitive to proton induced SET, but proton test results did not show any sensitivity for δVin greater than 12.5 mV [3]. An analysis has shown that the charge collection depth on these devices is greater than 10 µm [6]. Further, testing with Cf252 did not show any SET sensitivity, even when δV_{in} was reduced to 10 mV. This null result demonstrates that charge collection well beyond the range of fission fragments is necessary to produce transients in these devices. From all of this evidence, we conclude that proton induced SETs are not a concern for these devices.

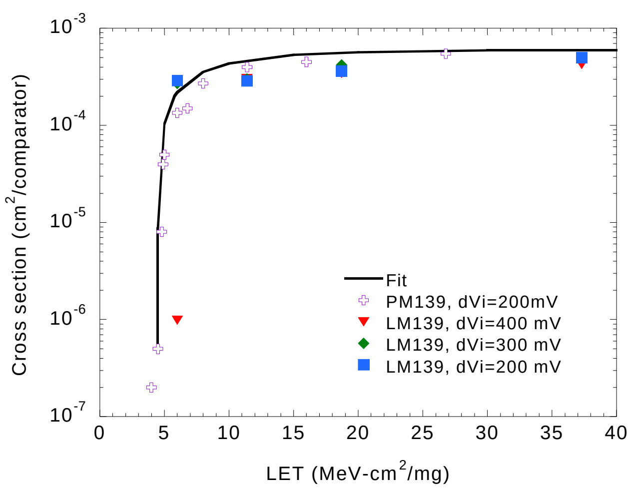

Fig. 5. PM139 and LM139 SET test data

B. SET rate calculation on MAP

The expected SET rates have been calculated with CREME96. CREME96 uses the Integral Rectangular Parallelepiped (IRPP) method. Three inputs are needed for the calculation: the device SET cross section curve as measured at a particle acceleration facility, the RPP device sensitive volume dimensions, and the predicted heavy ion environment for MAP in the form of an LET spectrum.

A Weibull fit of the SET cross section per comparator has been used to model the test data. The fit is shown in Fig. 5, and the fitting parameters are presented in Table I. The analysis of our data has shown that, in the application condition, 90% of the SETs have a rail to rail amplitude and the remaining 10% of transients have an amplitude larger than 2.5 V. Therefore all the transients may create a reset. Laser testing has identified different sensitive areas in the device, mainly in the input stage [5, 6]. Only one sensitive volume was considered for the calculation. This assumption leads to a conservative estimate of the rates. As charge collection depths are estimated to be greater than 10 µm [6], a range of sensitive volume thickness from 10 to 60 µm was used in the calculations.

TABLE I
SET CROSS SECTION FITTING PARAMETERS

Onset	4.5 MeVcm^2/mg
Saturated cross section	60000 µm^2
Width	4 MeVcm^2/mg
Power	0.8

The MAP spacecraft will be exposed to solar maximum conditions during all its mission life. To model the MAP galactic cosmic ray environment, we used the CREME96 model for solar maximum activity. To model a solar particle event, we used the CREME96 worst day model. The CREDO3/MPTB data have shown that the November 5 event was close to this model for LET up to 10 MeV-cm^2/mg. The shielding provided by the spacecraft provides minimal attenuation of the GCR, but may significantly attenuate the solar particles because their levels drop off at higher energies. Based on the MAP radiation analysis [8], the shielding surrounding the devices was estimated to be about 500 mils (12.7 mm) equivalent aluminum shielding. The radiation environments have been calculated with CREME96 for this value of aluminum shielding.

The results of the calculations are shown in Table II. The event rates are given for one comparator. The table shows that the GCR rate does not change significantly as a function of the sensitive volume thickness assumptions. On the average, we expect one GCR induced SET every 2 years implying that one GCR induced SET is probable during the 2-year mission.

TABLE II
SINGLE EVENT TRANSIENT RATES PREDICTED FOR THE MAP ORBIT

Shielding Thickness	**Sensitive Volume Thickness**	**GCR SET rate Solar maximum**	**Solar Event SET rate worst day**
(mils Al)	**(mm)**	**#/comp-day**	**#/comp-day**
500	10	1.8×10^{-03}	5.1×10^{-01}
	15	1.7×10^{-03}	3.0×10^{-01}
	20	1.6×10^{-03}	1.8×10^{-01}
	30	1.5×10^{-03}	6.5×10^{-02}
	40	1.3×10^{-03}	4.4×10^{-02}
	60	9.9×10^{-04}	3.4×10^{-02}

The SET rate increases significantly from background conditions (GCRs only) when the CREME96 worst day model is used to predict the solar particle environment. We can see that the rate also varies significantly as a function of the sensitive volume thickness assumptions. However, for most of cases that we used for the calculations, there is a high probability for a transient to occur during a solar particle event as defined the worst day CREME model.

V. Discussion

The analysis showed that the increased particle levels during large solar storm that occurred on November 4, 2001 are a probable cause for the hardware reset that put the spacecraft in safe-hold on November 5, 2001. A ground intervention, returned the spacecraft to the nominal observing mode. However approximately two days of science data was lost because of this anomaly. Therefore, the MAP project has implemented a space weather monitoring procedure to download the science data in case a solar particle event alert occurs. Today, after about one year of operation, no other anomaly has occurred since November 5, 2001.

A. Risk Management

Ideally the accommodation of radiation induced effects is accomplished in the design phase of system development. Projects can minimize risk of spacecraft malfunction or loss during the design phase by assigning a lead radiation engineer at the system level. The radiation engineer should follow a programmatic guide to address radiation issues that include defining the hazard, evaluating the effect of the hazard, defining requirements, evaluating device usage, and working with designers to get radiation tolerant designs [9]. The steps include screening parts lists and testing parts with unknown responses to radiation.

However, the use of more and more radiation-soft commercial-off-the-shelf (COTS) components and enabling technologies for space applications means that it is difficult and costly to design systems that are completely free from radiation effects. In an increasing number of cases, the effects can be minimized but not completely eliminated, especially during times when the radiation environment is enhanced by solar particle events, orbital passes through intense parts of radiation belts, or by particle acceleration during storms. When effects cannot be completely eliminated, the mission must assume a level of risk. This assumed risk is also managed by developing space weather guidelines that are used during the operation of the spacecraft to prevent deleterious effects.

B. Environment Modeling Tools

Radiation environment models that monitor and forecast the environment are essential tools for minimizing and managing risk. Prediction models are required for the spacecraft design phase to characterize the space weather "climate" by providing averages and extremes of the environment with good time resolution of variations. Probability distributions are also required so the level of risk can be assessed. While the CREME96 environment model is a significant improvement over the old CREME models, it is inadequate to address issues related to risk analysis. The CREME96 solar event models were based on the October 1989 solar particle event that was mainly a proton event. It has been shown that the CREME96 worst day model is a 90% worst case for solar protons [10], but a similar analysis does not exist for heavy ions. Also, new solar proton models are available to quantify how many proton events of a given amplitude can be expected for given mission durations and confidence levels [10], but no such tool exists for heavy ion events. After the MAP anomaly occurred, the project wanted to know how many heavy ion events like the November 4, 2001 event were expected for the next two years. Unfortunately, we do not have a model for heavy ions that can provide that information.

Real time environment monitors are also increasingly essential to diagnose on-orbit anomalies and to manage operational risks. The NOAA Space Environment Center (SEC) Space Weather Operations branch (SWO) performs this space weather monitoring. The information is available on their web site http://sec.noaa.gov where the SEC issues warning and alerts on space weather. For post anomaly resolution of single event effects, proton flux measurements from the GOES spacecraft are extremely useful.

NOAA defines strong or severe space weather events based on the >10 MeV proton flux levels. Fig. 6 shows the proton flux measurements of the main solar events of the current solar cycle that created significant effects on spacecraft [11, 12, 13,]. All of these events but the April 15, 2001 correspond to the strong or severe weather criteria as defined by NOAA. The April 15, 2001 event satisfies the moderate level criteria. However, the shielding materials surrounding electronics generally stop protons of energy lower than 30 MeV. Previous analyses of solar events showed that only the high-energy proton flux that can penetrate spacecraft shielding correlated to single event effects on spacecraft electronics [11, 14]. During all the events shown in Fig. 6, the > 100 MeV proton fluxes exceed the limit of 1 particle/s-sr-cm^2. Therefore, using the > 10 MeV alert may be too conservative whereas a > 100 MeV may be more appropriate for single event effects on spacecraft microelectronics.

NOAA provides very useful data about solar protons, but no real time information is available for high-energy solar heavy ions. Because single event effects are often caused by ions heavier than protons, readily available information about the heavy ion environment is also important for spacecraft operations. In the case of the MAP anomaly, ground testing showed that that the device was not sensitive to protons. To show that the anomaly was caused by solar particles, it was necessary to have detailed knowledge of the level of heavier ions. Fortunately, the MTPB/CREDO3 instrument data from November 5, 2001 event was provided by the Principal Investigator and was used to resolve the cause of the anomaly on MAP.

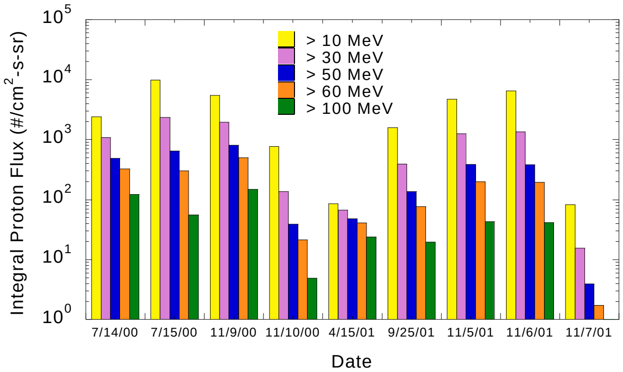

Fig. 6. Solar protons flux during the main solar particle events of the current solar cycle.

The CREDO3 data are also valuable to compare solar proton to heavy ion abundances during the current solar cycle. MPTPB/CREDO3 measurements showed that during the current solar cycle, three solar events (July 14 and 15, 2000; April 15, 2001; and November 5 and 6, 2001 [1]) had a strong heavy ion component. In Fig. 7 the particle fluxes for these events are compared to the CREME96 worst day model for LET < 10 MeV-cm^2/mg. It is possible that the large event of November 9, 2000 may have been comparable but data from MPTB were not obtained. The September 25, 2001 event is also plotted. Note that this event had significantly lower heavy ion fluxes (LET > 1 MeV-cm^2/mg) even though it was a severe proton event (LET <1 MeV-cm^2/mg). On the other hand, the April 15, 2001, a moderate proton event, shows the strongest heavy ion component, i.e., in the LET range from 1 to 10 MeV-cm^2/mg. Note that the fluxes of this event equal the CREME96 worst day model in this range.

Fig. 7 shows that proton information is not always adequate to monitor solar heavy ions because some events have a strong proton component and a small ion component and others have a small proton component and a very strong ion component. Solar weather monitoring based on low proton energy would have lead to a significant number of false alarms and the event of April 15, 2001 may have resulted in inadequate warnings. In the absence of real time heavy ion flux information, monitoring based on > 100 MeV protons, as it is now done for MAP, seems to be the best solution. During the current solar cycle, no heavy ion event would have been missed and only one false alarm would have occurred.

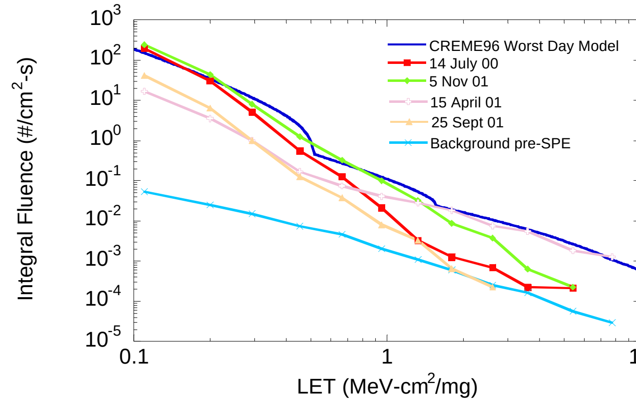

Fig. 7. Integral LET spectra as measured by CREDO3 on MPTB compared to the CREME96 worst day model.

VI. Conclusions

The calculated event rates show that a heavy ion SET on the PM139 in the reset circuitry is a possible cause for the MAP anomaly. The data from MPTB/CREDO3 have been of great help to analyze the space environment at the time of the anomaly. In order to mitigate possible loss of science data in the future, a solar weather monitoring procedure established by the MAP team has been implemented. If a significant increase of > 100 MeV proton flux is detected, the accumulated science data will be downloaded.

Analysis of MPTB/CREDO3 data has shown that it is not always adequate to monitor solar heavy ions with proton data. There is a need for an improved understanding of the statistical distribution of solar heavy ion events, and also improved forecasts including heavy ion flux measurements. There is also a need to improve the prediction methods for linear bipolar devices. Improved environmental measurements and linear device space experiments can accomplish this.

VII. Acknowledgment

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