Investigating Space Weather Events Impacting the Spitzer Space Telescope

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Our understanding of the dynamical process in the space environment has increased dramatically. A relatively new field of study called "Space Weather" has emerged in the last few decades. Fundamental to the study of space weather is an understanding of how space weather events such as solar flares and coronal mass ejections impact spacecraft in varying orbits and distances around the Sun. Specialized space weather satellite monitoring systems operated by the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA) allow scientists to predict space weather events affecting critical systems on and orbiting the Earth. However, the Spitzer Space Telescope is in an orbit far outside the areas covered by those space weather monitoring systems. This poses a challenge for the Spitzer's Mission Operations Team in determining whether space weather events affect Spitzer.

In order to form a coherent assessment of the space environment around the Spitzer spacecraft, the Spitzer Mission Operations Team must integrate real-time data collected from multiple space weather monitoring systems and analyze models and predictions based on those data. The Spitzer Mission Operations Team integrates those with the observed effects of space-weather-driven energetic particles that impact multiple subsystems on the Spitzer spacecraft, including the Mass Memory Card, the Star Tracker Assembly, the Solar Array, and Spitzer's main science instrument, the Infrared Array Camera.

The Spitzer Mission Operations Team's analysis of space weather events has demonstrated that a spacecraft whose primary function is not space weather can act as a space weather monitor. This is especially important for future astronomical and planetary missions whose orbits reach far beyond the Earth. Finally, the Spitzer Mission Operations Team can provide results to NASA and NOAA scientists and allow them to further refine their space weather models.

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Nomenclature

μm	=	micron (1 x 10^{-6} meter)
AU	=	astronomical unit
CME	=	coronal mass ejection
C&DH	=	command and data handling
EDL	=	entry, descent and landing mission phase
GOES	=	Geostationary Operational Environmental Satellite
hhmm	=	time format in hours and minutes
IRAC	=	infrared array camera
IRS	=	infrared spectrograph
IRU	=	inertial reference unit
iSWA	=	NASA integrated space weather analysis
MeV	=	mega electron volts (1 x 10^{6} electron volts)
MIPS	=	multi-band imaging spectrograph
MSL	=	Mars Science Laboratory (Curiosity rover) mission
NOAA	=	National Oceanic and Atmospheric Administration
pfu	=	proton flux units, number of particles sr-1 cm-2
radhits	=	short-hand for radiation damage event
SEU	=	single event upset
STF	=	abbreviation for Spitzer Space Telescope
SWRC	=	Space Weather Research Center
VMEbus	=	Versa Module Europa bus interface

I. Introduction

The Spitzer Space Telescope, one of NASA's Great Observatories, was launched in August 2003. Spitzer is managed by NASA's Jet Propulsion Laboratory (JPL), which shares mission operations with Lockheed Martin Space Systems Company (LMSSC) in Littleton, Colorado. Science planning is performed at the Spitzer Science Center located on the campus of the California Institute of Technology. As Spitzer enters its eleventh year of operations, the mission continues to operate well beyond its initial five year primary mission. One factor in the success of the Spitzer Space Telescope is the Mission Operation Team's approach to Space Weather.

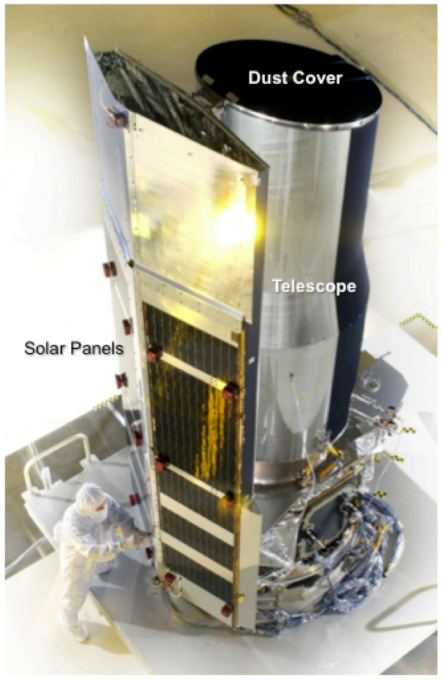


Figure 1. The Spitzer Space Telescope (photo courtesy of NASA).

A. Short Primer on Space Weather

Space Weather is a collective term used to describe space phenomena resulting from ambient plasma, magnetic fields, particle flows and radiation that alter the space environment, and impact space-based and earth-based systems. The primary source of the phenomena is the Sun. However, non-solar sources such as galactic cosmic rays are also included in the definition of space weather since they also produce high-energy particles affecting the space environment. As a field of study, space weather is highly inter-disciplinary, with theoretical roots in astrophysics and geophysics. Given its focus on the effects of space weather phenomena on engineered systems, it also has strong ties to electrical, mechanical, and aerospace engineering.

The ionized gas, or "plasma," that makes up the Sun generates a magnetic field from the Sun's rotational energy. This process, called the solar dynamo, is the source of all solar-produced space weather.[1] The Sun's plasma, and the magnetic field it carries, is convective. This convection, along with the rotation of the Sun itself, winds up the magnetic field to create a complex circulatory flow that flips the Sun's magnetic poles approximately every 11 years.[2] This 11-year variability of the Sun is called the "solar cycle".

Space weather practitioners often use the term "solar maximum," or just "solar max," to describe the point in the 11-year cycle at which the Sun reaches its peak activity. Conversely, solar minimum, or "solar min," is the point in the cycle at which solar activity is at its lowest point.

A solar flare is a process associated with rapid energy release in the Sun's outermost region called corona.[2] Flares emit energy across the electromagnetic spectrum, from radio to x-rays, and release high-energy particles that can contribute to space weather. A coronal mass ejection (CME), which may be released as a consequence of a solar flare,[2] is the loss of the Sun's mass through the ejection of plasma beyond the escape velocity of the sun. It is the large amount of high-energy particles contained within the ejected plasma that can cause harm to space-based and earth-based systems. The relationship between solar flares and CMEs is an area of active research. Most scientists agree that both solar flares and CMEs are a result of the release of magnetic energy in the corona.[2] Many spacecraft operators often use the terms "flare" and "CME" interchangeably.

Finally, a discussion of space weather processes would not be complete without discussing the solar wind. The solar wind is a plasma flow from the Sun that permeates throughout interplanetary space.[3] The magnetic field embedded in the solar wind resembles a spiral formed when water flows from a rotating sprinkler head (see, for example, Fig. 8). The solar wind is important to space weather because the galactic cosmic ray intensity also follows an 11-year cycle, but this cosmic ray cycle is out of phase with the solar cycle. One possible explanation is that the magnetic fields from the solar wind sweep away cosmic rays during solar max.[3]

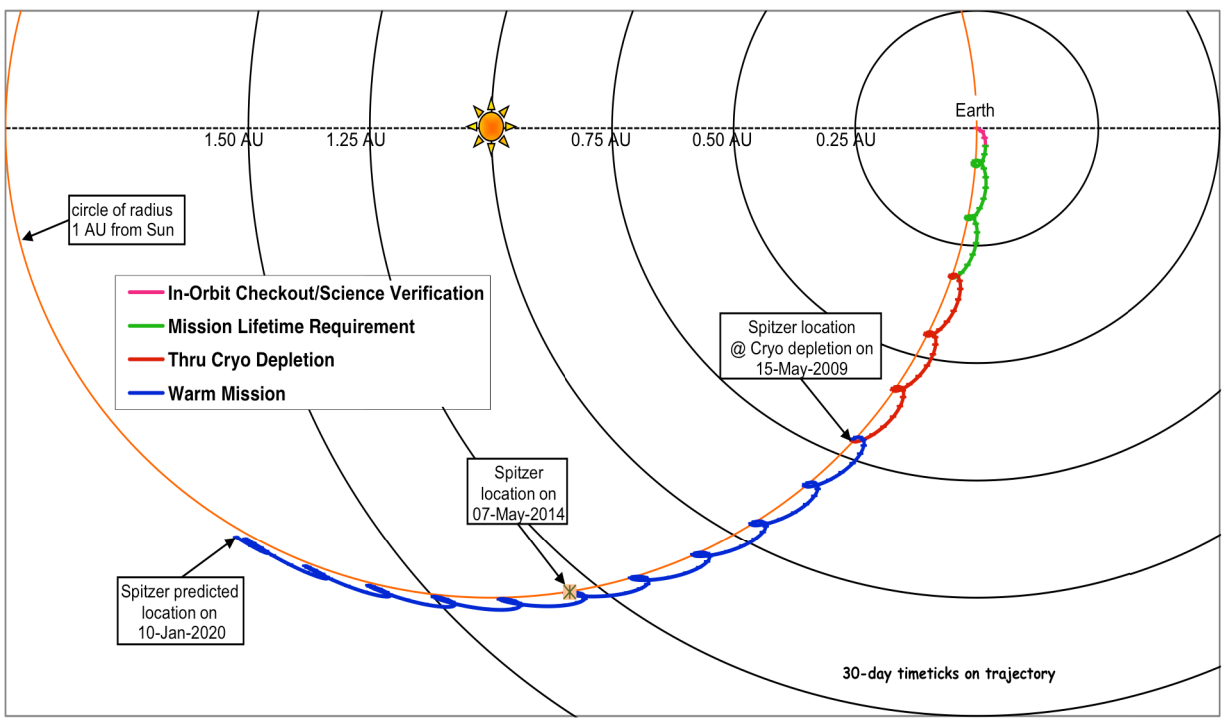


Figure 2. Spitzer's Earth-trailing orbit. Relative to the Earth, Spitzer has a looping path as it orbits the Sun along with the Earth.

B. Brief History of the Spitzer Space Telescope Mission

To achieve the scientific objectives of infrared astronomy, the space telescope was designed with a cryogenically cooled telescope attached to a multiple instrument chamber providing active cooling from 5.6 K to 12 K. The payload consists of three science instruments: the Infrared Array Camera (IRAC), the Infrared Spectrograph (IRS), and the Multi-band Imaging Photometer for Spitzer (MIPS)[4]. Although the liquid helium cryogen was eventually depleted, it is possible to continue operating the infrared space telescope in a passively cooled configuration. Analysis showed that, in this configuration, the thermal background of the telescope and the noise properties[5] of the two IRAC arrays provide sensitivity comparable to some of the observations made when Spitzer was still actively cooled. A science case[6] for an extended mission using the shortest wavelength cameras of IRAC was prepared, and NASA awarded a four-year post-cryogenic mission extension called the "Warm Mission." Spitzer project management is currently pursuing another Warm Mission extension.

C. Spitzer's Orbit and Position Relative to Space Weather Monitoring Satellites

Spitzer lies in a heliocentric, Earth-trailing orbit. Since its orbit is slightly more elliptical than the Earth's, it also slowly drifts away from the Earth at a rate of approximately 0.1 Astronomical Unit (AU) per year (Fig. 2). In the prime mission phase, when Spitzer was closer to the Earth, NOAA's Earth orbiting GOES satellites were able to provide warnings of impending space weather events that could impact Spitzer. After more than ten years of drifting away from the Earth, Spitzer's distance from Earth is greater than 1 AU, and the GOES satellites no longer serve as a predictive tool for Spitzer engineers. Nevertheless, GOES data are used for post-event analysis when engineers try to correlate possible Space Weather events with observed data.

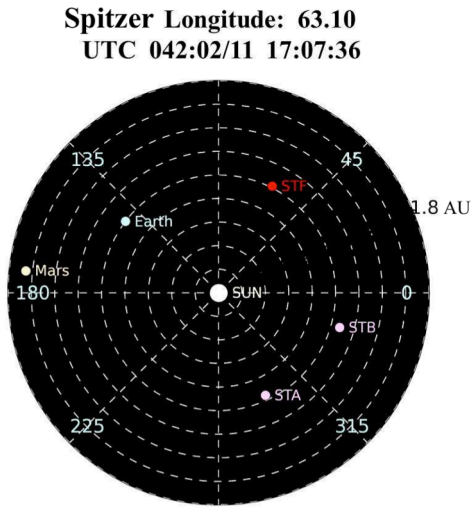


Figure 3. Spitzer's location (red "STF") relative to STEREO-A (STA) and STEREO-B (STB) Space Weather monitoring satellites as of Feb. 11, 2014.

A new generation of space weather monitoring satellites, called STEREO-A and STEREO-B, were launched in 2006. These satellites provided increased capabilities for detecting and monitoring Space Weather events. During Spitzer's prime mission phase, STEREO-B and Spitzer shared the same heliocentric Right Ascension; therefore, STEREO-B provided useful data to warn Spitzer of potential Space Weather impacts. However, Spitzer's current location places it far from both STEREO-A or STEREO-B, making data from those satellites less useful (Fig. 3).

II. Space Weather During Spitzer's Prime Mission

A. Protecting Common Electronics from Radiation Damage

Although Spitzer was designed with radiation-hardened shielding and tested to validate an assumed radiation environment based on a mission lifetime of five years, it was known the common electronics shared by MIPS and IRS could be susceptible to radiation damage. During the development of the space telescope, a system-level requirement was levied to create a contingency procedure to power off the common electronics in the event of a strong space weather event. Mission Operations Engineers then proceeded to develop a "Solar Flare" procedure. The procedure states that when the Spitzer project receives a NOAA Space Weather alert of an event producing protons exceeding the 100 MeV energy level and particle flux greater than 100 pfu, commands should be issued to place the spacecraft into stand-by mode, powering off the common electronics and the science instruments.

B. Space Weather Events and their Effects During Spitzer's Prime Mission

Spitzer experienced three noteworthy space weather events during the prime mission phase. In October and November 2003, just a few months after launch, the project received notifications from the NOAA space weather alert system that a CME had occurred at a level greater than the 100 pfu threshold. Given that the spacecraft was still in the in-orbit checkout phase of the mission, science instruments were already powered off, and no action was needed to protect the common electronics from damage. In January 2004, the project was alerted to another CME above the 100 pfu limit. Just as in 2003, this event coincided with science instruments powered off, but for a different reason: the spacecraft had already experienced a fault that had placed it in standby mode. Finally, in January 2005, data from the GOES space weather satellite indicated a high-energy proton event with a flux less than 100 pfu, but significant enough to potentially affect Spitzer. After performing a system-level trade analysis, the Spitzer Mission Operations Team decided not to place Spitzer into standby mode because the time it required to restore science operations would negatively affect Spitzer's expected observational efficiency during the prime cryogenic mission phase.

C. Subsystem Analysis of the Spitzer Prime Mission Space Weather Events

While the Spitzer Mission Operations team never executed the solar flare procedure during prime mission operations, the team did perform a post-event analysis based on data from Spitzer's subsystems. This analysis attempted to find anomalous data from Spitzer's subsystems that could be correlated with known space weather events identified by the Goddard Space Flight Center Space Weather Research Center (SWRC). For Spitzer, the subsystems that were identified to be more susceptible to CMEs are the Star Tracker Assembly (STA), the Solar Panel Assembly, and the Mass Memory Card (MMC). Additionally, space weather could also affect Spitzer's suite of science instruments.

To determine if the degraded data can be attributed to space weather, the Mission Operations Team must either link the event to a specific space weather event identified by the Goddard SWRC, or correlate by time with data from other spacecraft subsystems, which could indicate a single common source for all of the events. This is not always easy, since anomalous data can be a result of unrelated irregular behavior of a particular subsystem. These subsystem "idiosyncrasies" could occur at any time, even during a space weather event. The difficulties in analyzing subsystem data for space weather events are best illustrated through discussion of the STA.

III. Challenges in Data Analysis: The Star Tracker Assembly Example

The Spitzer Space Telescope uses Lockheed Martin Advanced Technology Center AST-301 STAs to provide attitude reference. The observatory carries two STAs – one active primary unit, and one inactive unit available as a backup in the event of a failure of the primary unit. During normal observatory operations, the STA provides an attitude reference with respect to the inertial reference frame, while a gyroscopic inertial reference unit (IRU) provides angular rate measurements.

Flight experience has shown that charged particles and radiation from CMEs and other solar events can affect the STA. Although the exact nature of the interference for any given event is unknown, charged particles can affect the STA in two ways: by causing single event upsets (SEU) in the STA's electronics, or by charging pixels in the CCD image sensor, which can lead to "false stars" in the resulting image and corruption of the attitude estimate. Of these two effects, SEUs, though not impossible, are usually less likely to be the cause of a given event, since the STA's electronics are radiation-hardened.

A. Non-Space Weather Factors

In addition to space weather, other factors can also interfere with the STA. Dense groupings of stars, such as the region around galactic center, or bright, moving objects, such as Jupiter or Saturn, can confuse the STA. Small-angle approximations in the STA's algorithms may also introduce errors during slews. The observatory has no method of determining the exact cause of these errors on its own, so the challenge to Spitzer's engineers lies in determining the likely causes of any STA errors from the range of potential causes using the limited amount of available telemetry.

Quaternion normalization errors, which are errors that affect the magnitude of the attitude quaternion calculated by the STA, are the most frequent errors exhibited by the instrument. An ideal attitude quaternion is expected to have a norm of one. The observatory's flight software calculates the norm of the attitude quaternion provided by the STA and, if the norm lies outside of a specified threshold around one, the attitude quaternion is declared invalid. These normalization errors occur frequently, sometimes up to several times per day during certain observations or operations. However, in spite of their high frequency, normalization errors usually cause little to no impact on the normal operation of the observatory. These errors usually persist for no longer than a single data sample. Furthermore, the observatory is able to operate over relatively long periods in the presence of these types of errors by integrating the angular rates from the IRU. Although the Mission Operations Team attempts to determine the cause of each of these errors, the high frequency and negligible impact of these occurrences has led to their classification as a known STA idiosyncrasy, and investigation rarely proceeds beyond initial disposition of the errors.

Larger, more persistent tracking errors may require the STA to transition through several operating modes in order to regain attitude knowledge. If the STA still fails to acquire attitude knowledge after spending a specified amount of time in its reacquisition mode, it will perform a soft reset in an attempt to clear any potential software errors and to restart the acquisition process. These larger errors occur much less frequently than the aforementioned normalization errors and usually number about half a dozen occurrences per year or less. Although larger errors usually do not impact normal observatory operations, the Mission Operations Team attempts to ensure that all instances are well understood.

B. Correlating STA Errors to Space Weather Events

Determining the likely cause of an error usually requires analysis of information originating outside of the raw STA telemetry. For instance, the observatory's attitude and body rates at the time of the occurrence can indicate whether the error may have been caused by a difficult sky region or by small-angle approximations during a slew. To determine whether an error was caused by solar events, the Mission Operations Team attempts to correlate the error to CME impact predictions and other measurements or anomalies outside of the STA. The team relies on WSA-ENLIL-CONE CME evolution model results, which are accessed from the NASA Space Weather Laboratory's "iNtegrated Space Weather Analysis" (iSWA) web application, to obtain predictions of CME impacts. Coincident events on other subsystems, such as correctible bit errors in the observatory's mass memory or an increase in the number of charged particle hits observed by IRAC, may suggest that a particular STA error was a result of a CME impacting the observatory. Occasionally, the investigation may even incorporate data from other spacecraft; in one instance, during a period in which Spitzer and the planet Mars were in alignment, the team was able to correlate data from Mars Odyssey's High Energy Neutron Detector (HEND) instrument to STA errors observed aboard Spitzer. Although STA operations are usually not adjusted in response to forecasts of CME impacts, the Mission Operations Team does maintain subscriptions to e-mail CME alerts provided by the Goddard SWRC. In the event that an alert message indicates that a CME will impact Spitzer, the team investigates STA telemetry after the event to look for large errors or an increased incidence of small normalization errors. Without help from space weather alerts and models, it is difficult to attribute STA errors to space weather.

IV. Spitzer's Science Instrument: The Infrared Array Camera (IRAC)

While the determination of space weather effects on the Spitzer STA has been elusive, Spitzer's science instrument during the Warm Mission era, IRAC, has displayed definitive evidence of space weather impacts. Unlike the STA, the IRAC uses two array detectors operating in the infrared wavelength regime at 3.6 μm and 4.5 μm. Whereas degraded data for both the STA and IRAC often manifest as a single saturated image pixel, damage to the IRAC observation can be more extensive.

A. Detecting Space Weather Events

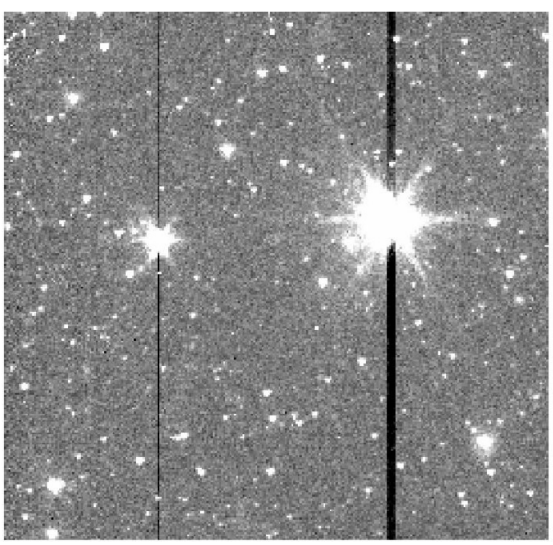


Figure 4a) . An Example of a 12 second observation taken with the IRAC 3.6 μm array. The two brightest sources have a large enough flux to cause a decrease in the flux along the entire readout array. This is called "a column pulldown."

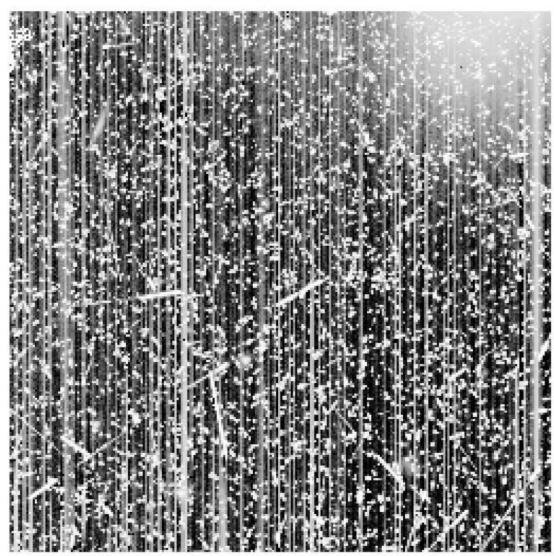


Figure 4b). An observation taken during an increase in proton flux displaying the streaks and column pulldown caused by impacts of high-energy particles.

Saturated star images on the IRAC are most often caused by a simple over-exposure in the infrared, not necessarily from space weather. In a saturated image, if the infrared flux on a single pixel is high enough, the readout of the entire column is affected. This effect, called "column pulldown," is visible in Fig. 4a). In that figure,

one pixel from each of the two saturated stars has exceeded the flux threshold on the pixel, and therefore depressed the flux from all the pixels in the column, along which the pixel values are read out. The pixel flux associated with the pulldown source can be modeled from the surrounding pixels, and therefore these astronomical based errors are easily correctable with standard data processing processes.

Extra-solar high-energy particles and cosmic rays are the primary space weather effects that impact IRAC. During a nominal observation, and in the absence of solar flares or CMEs, there are approximately four affected pixels per second. Occasionally, a normal cosmic ray will have enough energy to saturate a pixel on impact, and cause the column pulldown effect to occur. Due to the inability to model the flux of the cosmic ray, these column pulldowns cannot be corrected.

If a data frame is observed to have more than ten affected pixels, the team investigates to determine a possible origin. There is no directional information for these particle hits, so correlating a statistically raised number of particle hits with solar monitoring data helps to determine if the change is due to the solar component of space weather. A shower of high-energy particles, triggered by a large solar flare or CME, can lead to a substantial number of affected pixels, including a large number of saturated pixels. The saturated pixels will cause whole columns to display the column pulldown effect, and the combination of these effects will render data frames unusable, as demonstrated in Fig. 4b.

For the example in Fig. 4b, none of the column pulldown effects were associated with saturated star images. This implies the majority of the affected pixels were caused by high-energy particle hits. Moreover, this precluded any useful astronomical observation, but resulted in no permanent damage to the instrument. In its lifetime, IRAC has experienced only a few large CME events while powered on, as mentioned earlier. One of the largest occurred after a series of flares in January 2005.[7] Not every solar flare will be associated with a similar strength CME, but a handful of events have contained a high enough number of large energetic particles to cause disruption in the astronomical observations.

B. IRAC Team's Response to Space Weather Events

Due to incidences like those described above, the IRAC instrument team closely monitors solar flares to understand the overall effect before science data are released to the science investigator. Integration times for the full arrays can vary from 2 seconds to 100 seconds; therefore, single observations number in the thousands per day. For most observations, checking every frame is cumbersome, so an average of affected pixels is calculated over a single science observation period pointed at one part of the sky. This usually consists of between 20 and 1000 single frames of the same exposure time.

As part of the data processing pipeline, a mask file that keeps track of any problem pixels is created with every observation frame. Each frame is 256 by 256 pixels, and the mask is created with the same number of pixels, mirroring its associated observation frame. During processing, if a problem is found with a pixel or group of pixels in the observation, the same group in the pixel mask will be given a value associated with that problem. One such problem might be a cosmic ray, so an "outlier rejection" algorithm is used to compare multiple dithered frames stacked by astronomical, or sky, coordinates. As the telescope's viewpoint moves across the sky, an astronomical source will be observed in multiple pixels across the array, but a cosmic ray will only affect one pixel. When stacked by astronomical coordinates, the astronomical source should appear in multiple frames, so an "outlier" is a pixel with measurable flux only appearing in one of the frames. Those outlier pixels are then flagged as "radhits", marked in the pixel masks, and excluded when creating a mosaic, or image map, of the observations. This serves to create artifact-clean images while preserving the processing history.

During the ten year mission, the statistical baseline of average number of radhits per second has been established as approximately 4 hits per second, mostly due to cosmic rays. It has been observed that a slightly higher number of cosmic rays (approximately 5 hits per second) is detected during solar minimum, and a lower number is detected during solar maximum (just over 3 per second).

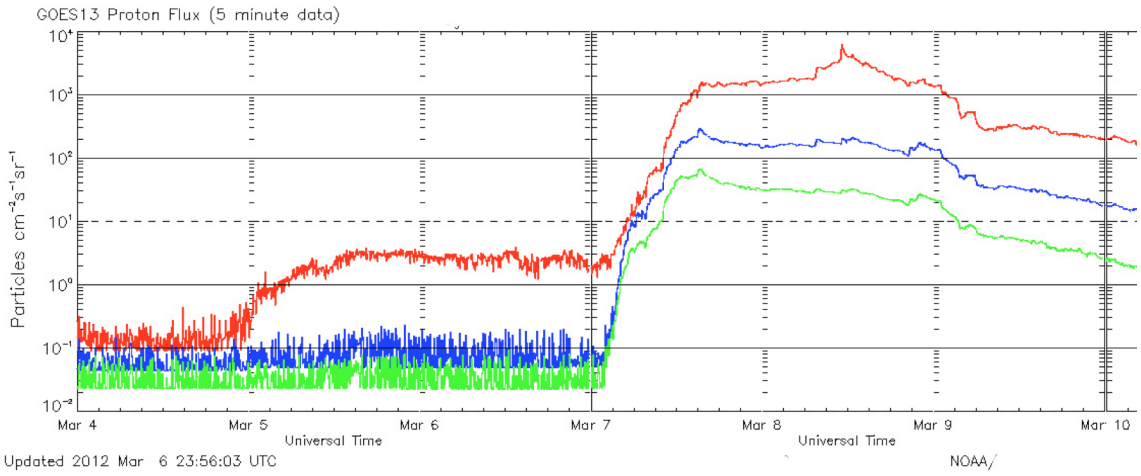


Figure 6a). The GOES 13 proton flux over the period during the March 5, 2012 flare in which the IRAC arrays were affected.

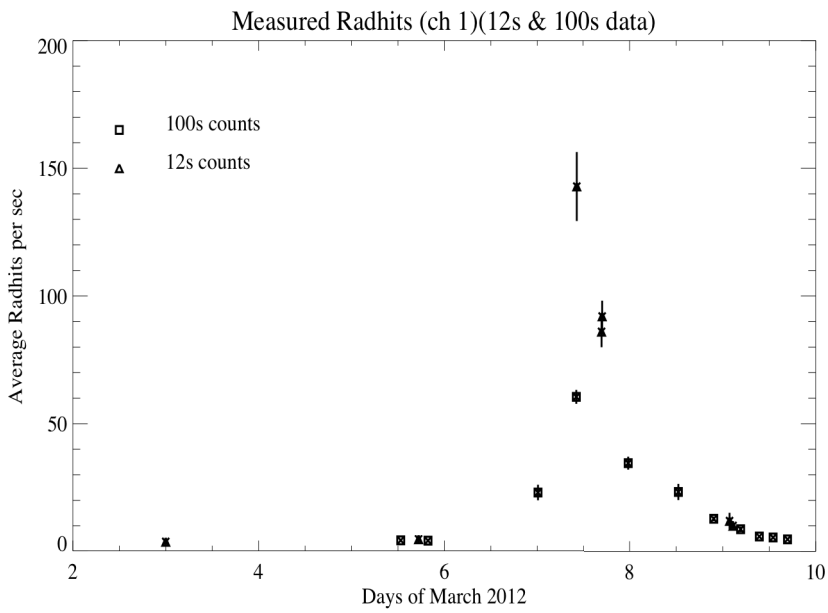


Figure 6b). The average number of cosmic ray hits per second detected by the arrays during the same period. Note the rise from approximately 4 per second to >150 per second detected shortly after the rise in the GOES 13 photon flux increase. Though the rise of cosmic ray hits is fast, it is brief, causing no prolonged effect.

C. Correlation with GOES Data

As shown in Fig. 6a and 6b, during the March 2012 solar flare and subsequent CME, the number of radiation hits per second measured by IRAC rose to over 150 shortly after > 100 MeV proton flux measured on GOES 13 rose above one particle cm^{-2} sr^{-1}. Unlike the GOES 13 measurements, the number of radiation hits measured by IRAC fell quickly after the maximum, due to the different locations of the Spitzer and Earth orbits. Since observations on IRAC are taken with varying exposure times, the 12 second, 30 second, and 100 second exposure time frame data are used to gain a good statistical measure of the hits per second.

Early in the mission, GOES data were used to provide a prediction of whether the spacecraft was going to be affected by space weather phenomena. However, as Spitzer has drifted farther away from Earth, GOES data are no longer indicative of the environment around Spitzer. Through the efforts of Joseph Hunt, Jr., working with the Goddard SWRC, the Spitzer orbital ephemeris is now included in the Goddard SWRC models. Whereas the

inclusion of the Spitzer ephemerides in the SWRC models, combined with data from the STEREO-A and STEREO-B spacecraft, provides the team with the necessary information on event timing, it cannot provide a total measure of particle flux at the spacecraft. For this reason, the WSA-ENLIL-CONE CME evolution model results are extremely helpful in providing predictions of CME impact timing. This allows an advanced warning capability for IRAC monitoring.

V. Spitzer Mass Memory Card (MMC)

The MMC is a solid state data recording unit, similar to the SEAKR P9 series recorders, located within the spacecraft's Command and Data Handling (C&DH) subsystem. The MMC is comprised of primary and secondary board assemblies that hold 8 Gbits of data each (16 Gbits total) and connect to the rest of the C&DH subsystem via a VMEbus interface. The primary and secondary MMCs are both powered on in the normal spacecraft operating mode. Both boards are accessible from the active C&DH side, but only one board can be written to or read from at a time. Critical parts within the MMC include dynamic random access memory (DRAM) chips and field-programmable gate assembly (FPGA) circuits. All critical components within the MMC are qualified for space operations, but the memory areas used for data storage are not radiation-hardened.

A. Nominal Operations of the MMC

Various tasks in the Spitzer flight software autonomously manage data on the MMCs. Some flight software tasks keep track of where data are located through pointers and lists, and onboard fault protection tasks ensure data integrity by regularly checking for errors. In addition, component-level fault protection routines continuously monitor MMC hardware health. While Spitzer is out of contact from Earth and performing scientific observations, all science instrument and engineering data are stored on the MMC for later playback during downlink sessions. Managing data on the MMC requires significant ground interaction due to the limited amount of storage space. The Mission Operations Team closely monitors MMC performance to gauge its current and long-term health, as well as to manually manage data storage. Manual data management involves marking data from the MMC that have already been transmitted and validated on the ground, removing transmitted data from the MMC in order to free up space for subsequent observations, and retransmitting data not successfully received during prior playback sessions. Estimated MMC usage is factored into science observation selection and planning.

B. MMC Error Detection and Correction

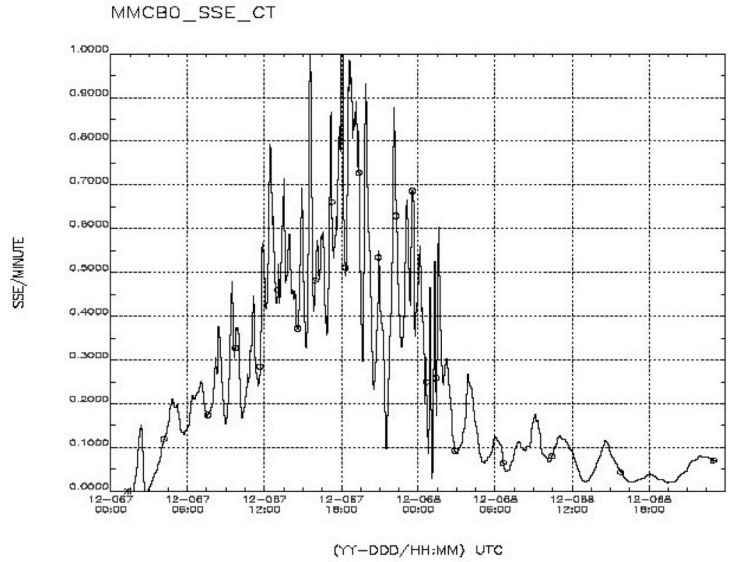
MMC data integrity is crucial. The onboard flight software continually monitors the state of the MMC and scrubs its two boards for data errors. Most MMC errors are "soft errors" that the flight software error scrubbing process is able to autonomously detect and then correct. A soft scrub error is defined as a single-bit error that the scrub process encounters at any memory location during its 4.5 minute (per board) cycle. Upon detecting a soft error, the scrub process automatically corrects it. Occasionally, the flight software encounters multi-bit errors at a single memory location that the scrub process cannot correct autonomously. Multi-bit errors can either be corrected by being overwritten with new data or through ground intervention. Neither type of error disrupts the normal function of the MMC.

C. Soft Scrub Errors and Space Weather Events

The absence of radiation hardening for its data storage areas causes the MMC to be more susceptible to changes in the space environment than other spacecraft components. Soft scrub error count increases are among the most observable MMC responses to space weather effects. Observable spikes in MMC soft scrub error counts can be directly tied to flares or CMEs that reach Spitzer's location.

A complicating factor, however, is that one or more memory locations on Board 0 consistently generates higher numbers of soft scrub errors. These faulty memory locations drive up the soft scrub error count rate, making it more difficult for the Mission Operations Team to differentiate between this increased background "noise" and the rapid changes in soft scrub error rates that are indicative of space weather events. This faulty memory location issue does not affect MMC Board 1.

The Mission Operations Team keeps daily track of soft scrub error counts; not only to monitor MMC data integrity, but to identify space weather events as well. Figure 7a and 7b display soft scrub error counts during a two day period in early March 2012, when the arrival of a CME event in the vicinity of Spitzer, as shown in Fig. 8 and Fig. 9, corresponded with a major increase in MMC soft scrub error counts. The event shown in Fig. 8 and Fig. 9 not only affected the MMC, but also caused increased noise in the IRAC instrument science images.



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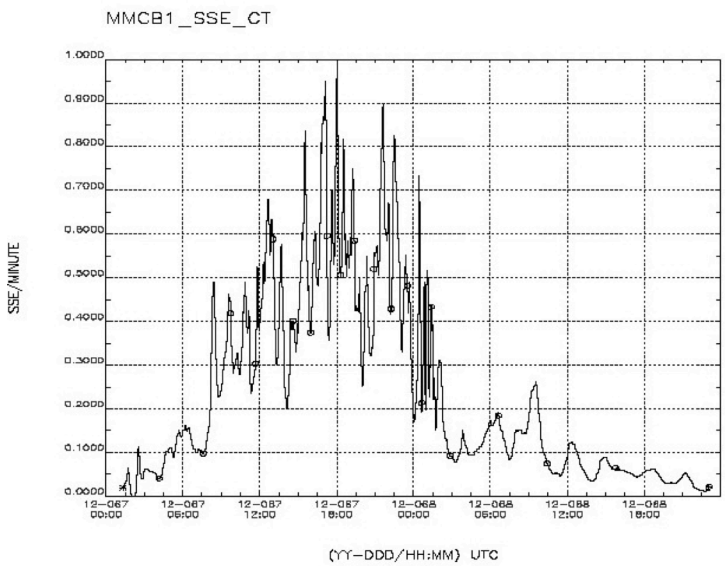

7b)

Figure 7a) and b). Spitzer MMC Board 0 and Board 1 Soft Scrub Error Counts during March 7-8, 2012 CME Event

D. Multi-bit Errors and Space Weather Events

Space weather can also cause multi-bit MMC errors. As mentioned before, the MMC error scrubbing process cannot correct this type of error. When the error-scrubbing task detects two or more bit errors at a given MMC Board 0 or Board 1 memory location, the location is reported as uncorrectable. Multi-bit errors can be corrected without ground intervention when new data are written to the MMC. Board 0 multi-bit errors are most often corrected this way because it is the most heavily used of the two MMC boards. In particular, if a multi-bit error occurs in Board 1, where new data are unlikely to be written, the error must be manually overwritten by specialized commands sent from the ground.

Single event upsets by highly energetic particles are the most likely cause of multi-bit MMC errors. At 17:16:30 UTC on March 7, 2012, at the peak of the MMC soft scrub error counts shown in Fig. 7a and 7b, MMC Board 1 experienced a multi-bit error.

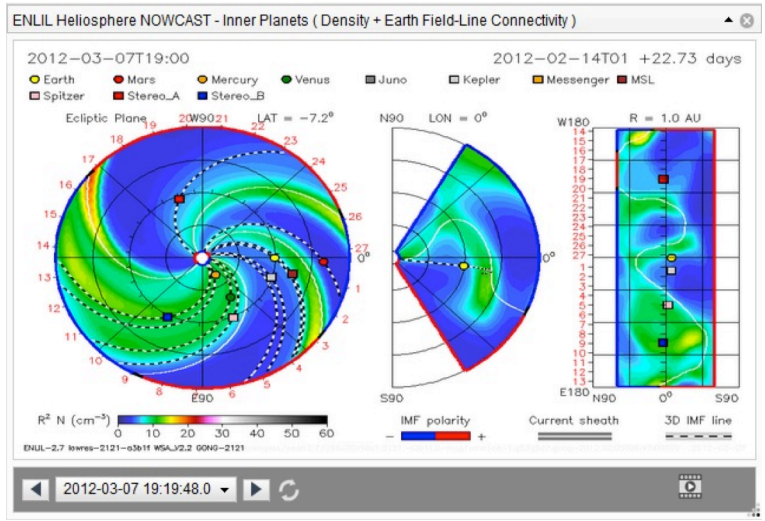

Figure 8. iSWA ENLIL Heliosphere Inner Planets Simulation of March 8, 2012 CME Event[8]

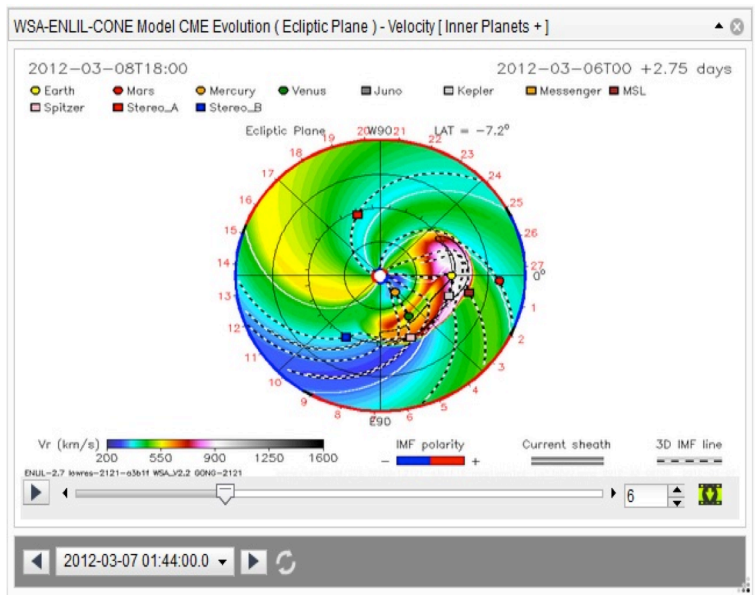

Figure 9. iSWAS WSA-ENLIL-CONE Model CME Evolution Simulation of March 7-8, 2012 CME Event[8]

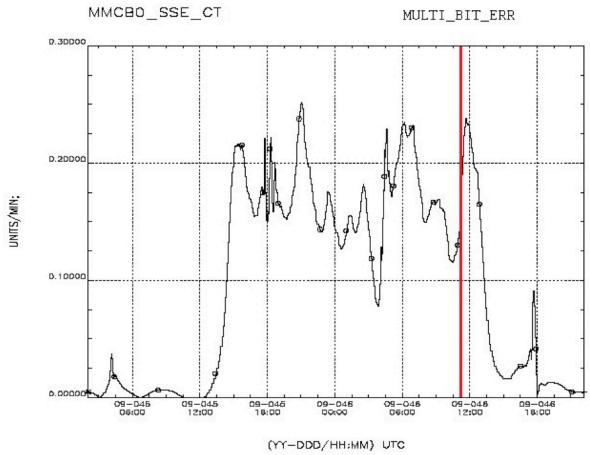

Figure 10a). February 15, 2009 MMC Board 0 multi-Bit Error, indicated by the vertical red line.

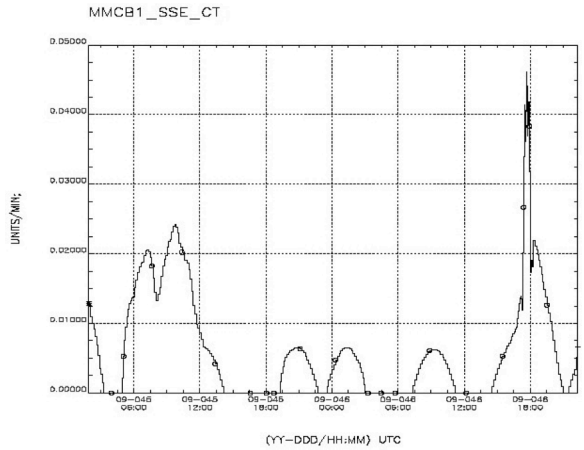

Figure 10b). In the same February 15, 2009 event, an increase in soft scrub errors was seen in MMC Board 1. This correlates well with the multi-bit error in Fig. 10a), and indicates a possible space weather event.

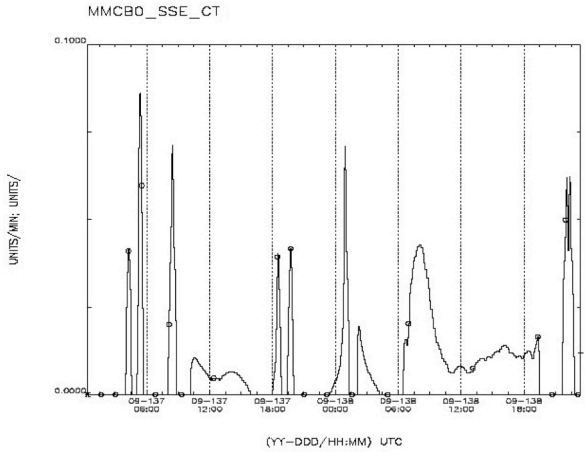

Figure 11a). A relatively small increase in MMC Board 0 soft scrub error was seen on May 18, 2009, a relatively quiescent period of space weather activity.

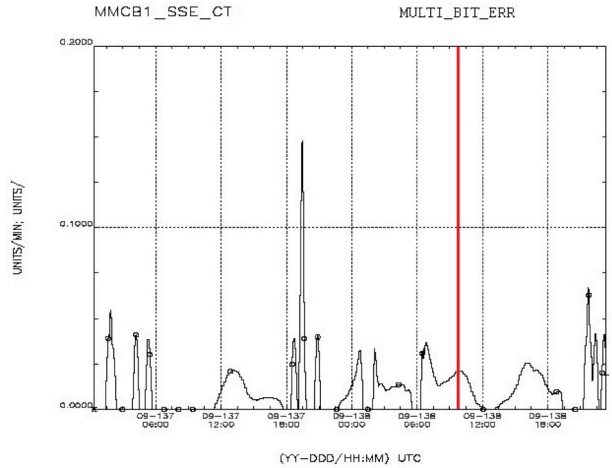

Figure 11b). In the same May 18, 2009 event, the vertical red line indicates a multi-bit error. Note both Fig. 11 a) and b) events occurred without a Goddard SWRC alert. This may indicate extra-solar cosmic ray origin.

Not all MMC errors occur during periods of high solar activity. During a period in 2009 when solar activity was relatively low due to a solar minimum occurring in the previous year, MMC Board 0 and Board 1 multi-bit errors still occurred. These multi-bit MMC errors observed in 2009 may have been caused instead by extra-solar cosmic rays. The frequency of cosmic rays is believed to increase when solar activity is low.[9] The only MMC error event in 2009 that roughly correlated with a space weather event (electron flux > 2MeV) occurred on February 15, when a moderate increase in Board 0 soft scrub errors and a multi-bit error on the same board occurred (Fig. 10a-b).[10]A more typical MMC multi-bit error occurred on Board 1 on May 18, 2009. In this instance, there were no corresponding space weather alerts, and only a very slight uptick was observed in soft scrub errors (Fig. 11a-b).[11]

After more than a decade in space, the Spitzer Space Telescope's MMC hardware continues to operate robustly and reliably. The MMC has also proven highly resilient to the hazards posed by space weather events, and offers a unique insight into Spitzer's immediate space environment. The MMC's autonomous error detection/correction routines mitigate the vast majority of soft data corruption occurrences caused by space weather. On the rare occasions that the MMC experiences multi-bit errors that require manual intervention, the Mission Operations Team has procedures in place to overwrite the affected memory locations.

VI. The Spitzer Solar Panel Assembly

Electrical power for the Spitzer Space Telescope is provided by the solar panel assembly. It consists of two solar panels, each 320 cm by 72 cm (10.5' x 2.4'). The solar panel assembly was designed to generate a maximum (at perihelion) power output of 467 watts at launch, and, based on cell degradation models, would still be able to generate a maximum of 434W at the predicted end of the cryogenic mission (launch plus 4.5 years), which represents a 7% decline over that period. At present, almost 4.5 years after the end of the cryogenic mission, the solar panel assembly generates 410W at perihelion and 393W at aphelion, which provides a margin of roughly 19W over the bus power load requirement.

The major concern pertaining to solar panel assembly operation is degradation over time. A key mechanism for solar cell degradation is solar radiation, particularly ultraviolet (UV) radiation. The main effect of UV radiation upon the solar panel assembly is to diminish the optical properties of the cover glass, which typically happens during the first few months in space. Solar radiation also degrades solar cell materials through numerous ionization-related effects, primarily from incident proton fluence. The reduction of transmittance of the cover glass through darkening is caused by the formation of color centers in the glass and/or oxide materials. Radiation damage produces several effects in the organic cell materials from trapped charges which increase leakage current, electron, proton, and neutron displacement damage. [12]

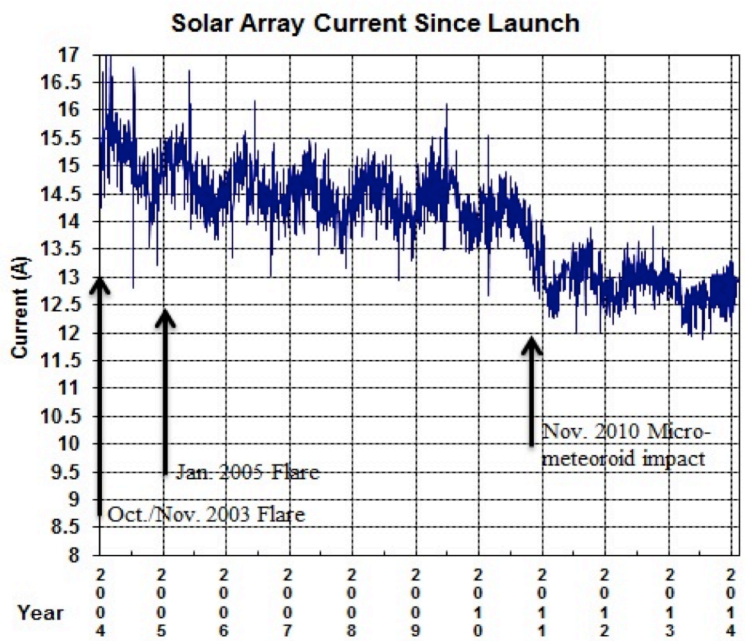

Figure 12. Solar Panel Assembly (solar array)

As previously mentioned, the arrays were predicted to degrade over time, but this prediction was based upon a steady-state solar radiation model. However, space weather events have the capacity to accelerate solar cell degradation. In the case of Spitzer, major solar weather events in October-November 2003 and January 2005 diminished the solar panel assembly output by 4.7% and 2.8%, respectively. In addition, in early November 2010, a micrometeoroid impact damaged one of the solar panel assembly's strings, reducing the total power output by an additional 6.5% (Fig. 12).

The Spitzer Space Telescope's solar panel assembly has provided ample power margin for all spacecraft and science instrument operations since launch. With Spitzer now into its second decade of operations, the combined effect of generalized solar cell degradation and sudden, adverse space weather events will eventually lead to the solar panel assembly no longer being able to provide sufficient power margin to power all subsystems continuously. Eventually, periods of peak power loads will cause the battery to discharge, which will in turn require periods of Spitzer's operational schedule to be reserved for battery recharging. Future operations could also possibly entail more drastic power saving regimes.

VII. Taking a System-Level Approach in Spitzer's Warm Mission

Determining whether a particular anomalous or degraded data set was a result of space weather is not always easy. False stars seen on the STA could be a result from a space weather event, or could simply be from known idiosyncratic behavior in the STA subsystem. For both the IRAC and the MMC, space weather effects are more readily observable, yet even those subsystems generate their own anomalous artifacts that have no connection to space weather events. Furthermore, the original requirement to protect the common electronics of the MIPS and IRS science instruments has become outdated because those instruments are powered off in Spitzer's Warm Mission phase. For these reasons, the Spitzer Mission Operations Team needed a new method to address the space weather concern during Spitzer's Warm Mission.

For the new space weather process, the Mission Operations Team implemented a system-level approach, which integrated independent subsystem anomaly reports into one master report. This new process allows any team member to determine, at a glance, whether an anomalous data set seen on one Spitzer spacecraft subsystem is also seen on another subsystem. More importantly, the new process provides data to correlate anomalous subsystem data to a Goddard SWRC space weather alert, if it exists. In February 2012, Spitzer implemented the Integrated Warm Mission Space Weather Process.

A. The Integrated Warm Mission Space Weather Process

The Integrated Warm Mission Space Weather Process begins with the receipt of a space weather alert message. The alerts received in the Warm Mission are alerts from the Goddard SWRC, which now uses more accurate space weather models than those used in prime mission phase, and include Spitzer's ephemeris in their visualization tool. Moreover, the alerts specify if an impact to Spitzer is likely. If an impact to Spitzer is predicted, the Mission Operations Team documents the event using an existing JPL anomaly tracking tool.

Whereas the space weather related anomaly reports in the prime mission phase were generated separately by whichever subsystem team reported the anomalous behavior, the system-level approach in the Warm Mission provides a single master anomaly report which integrates results from all subsystems affected by the space weather event. With the alert message providing the expected time of the CME's leading edge impact, the Mission Operations Team can anticipate when data containing possible CME signatures will be downlinked, and plan to make an impact assessment in the subsystem data. Not all alerts imply a direct impact to Spitzer, and, in most cases, only an update to the problem report is required.

Given the system-level approach now being used in the Warm Mission, any strange signatures encountered by the subsystem are required to be documented in the master anomaly report. Therefore, the integrated process also allows documentation of anomalies that may be related to space weather, but do not match up to any of the received Goddard SWRC space weather alerts.

B. The Integrated Warm Mission Space Weather Spreadsheet

In addition to the master anomaly report, the Integrated Warm Mission Space Weather Process also produces a report summary in the form of an Excel spreadsheet. The spreadsheet (Fig. 15) acts as a database of possible space weather events seen on Spitzer. Since the spreadsheet is only a summary, a detailed description of the error can be found in the full anomaly report. The spreadsheet columns include:

1. *Item number*

   This is the item number of a possible space weather event

2. *Title*

   The spreadsheet contains two types of entries: events corresponding to a space weather alert message and events not corresponding to a space weather alert message. Those two types of entries are distinguished from each other by different prefixes in the Event Title: SWE for Space Weather Event and NSE for Non-Alert Space Weather Event. The rest of the Event Title field describes the year, month and day of the year of the event message or non-alert event.

3. *Message*

   If the event is associated with a Goddard SWRC space weather alert, then the alert message identification number is provided.

4. *Activity ID*

   This is also a Goddard SWRC space weather alert field. It provides additional identifying information about the space weather event.

5. *Edge Time*

Event		Description Section Space Weather Alert Message				Spacecraft Analysis Section				Instrument
Item #	Title	Message	Activity ID	Edge Time	Class	Alarms	MMC Soft Scrub Errors	Star Tracker	Power	IRAC
1	NSE_2012-0215_044	None	N/A	N/A	N/A	No	Board 1	No	No	No
2	SWE_2012-0307_067	ID: #20120307-AL-009	----	069 / 0837	O	B1-DBE	Board 0 & 1	No	No	Plot (LS)
3	SWE_2012-0327_087	ID: #20120327-AL-003	----	088 / 1726	O	Yes	Nominal	Printout	No	No
4	SWE_2012-0416_107	ID: #20120416-AL-001	2012-04-16T18:10:00-CME-001	109 / 1523	O	Yes	Nominal	No	S/A Plot	No
5	SWE_2012-0512_133	ID: #20120512-AL-002	2012-05-11T23:54:00-CME-001 2012-05-12T01:54:00-CME-001	135 / 1428	O C	No	Board 0	No	No	No
6	NSE_2012-0517_138	ID: #20120517-AL-004	2012-05-17T:01:48:00-CME-001	150 / 1140	O	Yes	Nominal	No	No	Plot
7	SWE_2012-0527_148	ID: #20120527-AL-003	2012-05-27T:06:24:00-CME-001	150 / 1140	C	Yes	Nominal	Timeline (FI)	No	No
8	SWE_2012-0614_166	ID: #20120614-AL-002	2012-06-14T14:09:00-CME-002	169 / 1704	C	No	Nominal	No	No	No
9	NSE_2012-0624_176	None	N/A	N/A	N/A	No	Board 1	No	No	—
10	SWE_2012-0712_194	ID: #20120712-AL-006	2012-07-12T16:54:00-CME-001	196 / 1356	O	No	Nominal	No	No	---
11	SWE_2012-0728_210	ID: #20120729-AL-001	2012-07-28T21:24:00-CME-001	213 / 1252	C	No	Nominal	No	No	—
12	SWE_2012-0831_244	ID: #20120831-AL-003	2012-08-31T20:36:00-CME-001	246 / 0054	O	No	Nominal	No	No	—
13	NSE_2012-0906_250	None	N/A	N/A	N/A	B1-DBE	Nominal	No	No	No
14	SWE_2012-0924_268	ID: # 20120924-AL-001	2012-09-23T15:12:00-CME-001	270 / 0008	O	No	Nominal	No	No	No
15	SWE_2012-0928_272	ID: # 20120928-AL-001	2012-09-28T02:25:00-CME-001	275 / 0156	O	No	Nominal	Spike	No	No
16	NSE_2012-1017_291	None	N/A	N/A	N/A	B0-DBE	Nominal	No	No	No
17	NSE_2012-1027_301	None	N/A	N/A	N/A	No	Board 0	No	No	No
18	NSE_2012-1028_302	None	N/A	N/A	N/A	No	Board 0	No	No	—
20	SWE_2012-1108_313	ID: # 20121108-AL-003	2012-11-08T11:09:00-CME-001	316 / 0012	O	No				
21	SWE_2013-0123_023	ID: # 20130123-AL-001	2013-01-23T14:55:00-CME-001	026 / 1126	C	No	Nominal	No	No	No
22	NSE_2013-0210_041	None	N/A	041 /0000	N/A	No	IDIO	drop Acq	No	Yes

Figure 15. The Integrated Warm Mission Space Weather Spreadsheet

This is another Goddard SWRC space weather alert field. It is the SWRC predicted time when the leading edge is expected to impact Spitzer. The time field is formatted as day of the year/hhmm.

6. Class

The final Goddard SWRC space weather alert field, this describes the classification of the space weather event.

7. Alarms

The first field in the spacecraft analysis section, this field lists the identification codes of any spacecraft red alarms seen during the event.

8. MMC Soft Scrub Errors

A sudden increase in the soft scrub error rate could indicate a space weather event. This column records the MMC board or boards (either Board 0 or 1, or both) on which the error occurred.

9. Star Tracker (STA)

Several types of errors can occur in the STA, and when one of those errors happens during a possible space weather event, then this column records the type of error. The terminology in this field refers to a shorthand description referencing details in the full anomaly report. Furthermore, if the error temporarily affected the functionality of the STA, the abbreviation "FI" is added.

10. Power

The Power column refers to the Solar Panel Assembly. If anomalous data is seen in the solar panels, and the anomaly is associated with a space weather event, then just as in the STA column, a shorthand description of the error is noted.

11. IRAC

The only science instrument operating during Spitzer's Warm Mission is IRAC. If an error is correlated with a space weather event, then the error is noted in this column using a shorthand notation that references the full anomaly report. If the error causes a loss of science, then the abbreviation "LS" is added.

VIII. Conclusion

Space Missions have benefitted from the space weather forecasting tools provided by NASA and NOAA. The continued success of the Spitzer Space Telescope mission, now operating for more than six years beyond its primary mission phase, requires the Mission Operations Team to characterize long-term spacecraft subsystem performance; in particular, the team must be able to determine the causes of anomalous data seen in subsystem trending analysis. The NASA/NOAA space weather alerts and forecasts give engineers the ability to correlate anomalous data with naturally occurring space weather phenomena. Additionally, using Spitzer's Integrated Warm Mission Space Weather Spreadsheet, the team can easily correlate an anomalous data set seen on one spacecraft subsystem to data from another subsystem, further increasing confidence in their ability to rule out unrelated subsystem faults during space weather events.

By following the Integrated Warm Mission Space Weather Process, Spitzer can provide space weather activity monitoring information in some situations. For example, in 2012, Spitzer was asked by the Mars Science Laboratory (MSL) Mission's Entry Descent and Landing (EDL) team to provide an extra analysis into the level of solar energetic particle flux between the Sun and Mars during their critical EDL phase. MSL made the request due to Spitzer's ideal location between the Sun and Mars at the time of EDL. As EDL day approached, space weather forecasts indicated a slow-moving CME advancing towards Spitzer, and heading towards Mars. Spitzer provided MMC soft scrub error plots to the MSL EDL team prior to the start and during the execution of the EDL phase. Fortunately, none of the plots provided to MSL showed an increase in soft scrub errors. The Warm Mission Space Weather Spreadsheet also did not document any anomalies on any other Spitzer subsystems, which increased the reliability of the MMC data. The Spitzer Space Telescope was designed without any dedicated space weather radiation detectors, and its ability to help a NASA flagship mission, like MSL, in monitoring space weather was likely never envisioned by Spitzer's designers. This is the essence of innovation in space operations.

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