3.6 SPACE WEATHER EFFECTS ON SOHO AND ITS LEADING ROLE IN THE EARLY-WARNING SYSTEM FOR SPACE WEATHER

P. Brekke*, B. Fleck, S.V. Haugan, RSSD, European Space Agency
T. van Overbeek, H. Schweitzer, SCI-P, European Space Agency
M. Chaloupy, Astrium, GSFC

1. INTRODUCTION

Since its launch on 2 December 1995, the Solar and Heliospheric Observatory (SOHO) has provided an unparalleled breadth and depth of information about the Sun, from its interior, through the hot and dynamic atmosphere, and out to the solar wind. In addition SOHO has several times demonstrated its leading role in the early-warning system for space weather. SOHO is in a halo orbit around the L1 Lagrangian point where it views the Sun 24 hours a day. Thus, it is situated outside the Earth's protective magnetosphere which shields other satellites from high energy particles and the solar wind. We present a summary of the observed effects on the instruments and electronics on SOHO throughout the mission. In particular we focus on a number of large particle events during the recent years while the Sun was approaching maximum activity, and how they affected both the scientific data as well as hardware components.

2. THE SOHO SPACECRAFT

The SOHO mission is a major element of the International Solar Terrestrial Programme* (ISTP), and, together with Cluster, forms the Solar Terrestrial Science Programme (STSP), the first cornerstone in ESA's long-term science programme 'Horizons 2000' (Domingo, Fleck, and Poland 1995). ESA was responsible for the spacecraft's procurement, integration and testing. It was built in Europe by an industry team lead by Matra Marconi Space (now called Astrium). Weighing in at 1,850 kg, the SOHO spacecraft measures about 9.5 m across with its solar panels extended and is 4.3 m high. Figure 1 provides a schematic view of the SOHO spacecraft. NASA provided the launcher, launch services and ground-segment system and is responsible for in-flight operations. Mission operations are conducted from NASA/Goddard Space Flight Center (GSFC).

SOHO was launched by an Atlas II-AS from Cape Canaveral on 2 December 1995 and was inserted into its halo orbit around the L1 Lagrangian point on 14 February 1996, six weeks ahead of schedule. Commissioning of the spacecraft and the scientific payload was completed by the end of March 1996. The launch was so accurate and the orbital manoeuvres were so efficient that enough fuel remains on board to maintain the halo orbit for several decades, many times the lifetime originally foreseen. An extension of the SOHO mission for a period of five years beyond its nominal mission duration (2 years), i.e. until March 2003, was approved in 1997 by ESA's Science Programme Committee (SPC). A second extension of another four years, i.e. until March 2007, was granted by the SPC in 2002. This will allow SOHO to cover a complete 11-year solar cycle.

SOHO has a unique mode of operations, with a "live" display of data on the scientists' workstations at the SOHO Experimenters' Operations Facility (EOF) at NASA/Goddard Space Flight Center, where the scientists can command their instruments in real-time, directly from their workstations.

SOHO enjoys a remarkable "market share" in the worldwide solar physics community: over 1500 papers in refereed journals and over 1500 papers in conference proceedings and other publications, representing the work of over 1500 scientists.

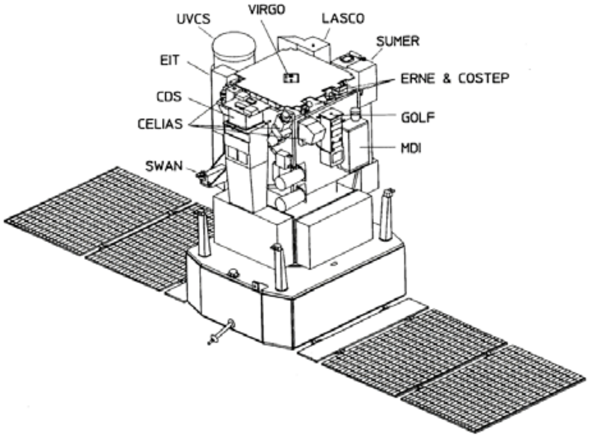

Figure 1. SOHO spacecraft schematic view.

3. SOHO A SPACE WEATHER WATCH DOG

Observations of the solar corona with the Large Angle Spectrometric Coronagraph (LASCO) and the Extreme ultraviolet Imaging Telescope (EIT) instruments on SOHO provide an unprecedented opportunity for continuous real-time monitoring of solar eruptions that affect space weather. LASCO takes images of the solar corona by blocking the

---

* Corresponding author address:
Paal Brekke, RSSD, European Space Agency
NASA/GSFC, Greenbelt, MD 20771
USA, Phone: (301) 286-6983, Fax: (301) 286-0264
Email: pbrekke@esa.nasxom.nasa.gov

light coming directly from the Sun itself with an occulter disk, creating an artificial eclipse within the instrument. LASCO best observes limb CMEs, but its high sensitivity even allows unprecedented detection of halo CMEs. EIT provides images of the solar atmosphere at four extreme ultraviolet wavelengths and reveals flares and other associated events in the atmosphere. EIT can usually determine whether CMEs seen by LASCO originated on the near or far side of the Sun, based on the presence or absence of corresponding events on the near side.

LASCO has been collecting an extensive database for establishing the best statistics ever on CMEs and their geomagnetic effects. By June 2003 more than 6000 CMEs have been recorded[*]. CMEs are vast structures of plasma and magnetic fields that are expelled from the Sun. CMEs moving outward from the Sun along the Sun-Earth line can, in principle, be detected when they have expanded to a size that exceeds the diameter of the coronagraphs occulting disk. CMEs directed toward or away from the Earth should appear as expanding halo-like brightenings surrounding the occulter. An example of a halo-CME is shown in Figure 2 as recorded by the LASCO C3 detector on 6 June 2000. Although halo CMEs were discovered by the SOLWIND coronagraph two solar cycles ago (Howard et al., 1982) the LASCO experiment is the first to observe a significant number of these events, thanks to its extended field of view and its improved sensitivity compared with earlier coronagraphs.

St.Cyr et al. (2000) reported the properties of all the 841 CMEs observed by the LASCO C2 and C3 white-light coronagraphs from January 1996 through the SOHO mission interruption in June 1998 and compared those properties to previous observations by other instruments. The CME rate for solar minimum conditions was slightly higher than had been reported for previous solar cycles, but both the rate and the distribution of apparent locations of CMEs varied during this period as expected. While the pointing stability provided by the SOHO platform in its L1 orbit and the use of CCD detectors have resulted in superior brightness sensitivity for LASCO over earlier coronagraphs, they have not detected a significant population of fainter CMEs. The general shape of the distribution of apparent sizes for LASCO CMEs is similar to those of earlier reports, but the average and median apparent size of 72° (50°) is significantly larger.

3.1 SOHO's Role at the Space Environment Center

The Space Weather Operations Center at the Space Environment Center (SEC) in Boulder uses SOHO images daily. The forecast operations have become to rely on SOHO on a routine basis as a key input to solar observing and geomagnetic forecasting. LASCO is the only direct observation of coronal mass ejections. Prior to LASCO they had to rely on activity they knew to be well associated with CMEs, but none of these associations are 100% reliable. They use direction, size, and velocity information in LASCO images to help determine the arrival time and effectiveness of the disturbance.

EIT also plays an important role at SEC to pin down the source of any eruption. In addition EIT is a very good source for identifying erupting prominences and to identify coronal hole locations. Coronal holes have become an increasingly important part of the geomagnetic forecasting process. In fact at this point in the solar cycle coronal hole activity has become the predominant driver of geomagnetic activity.

Finally, forecasters use the MDI data on SOHO in order to track sunspot growth and decay and the magnetograms are used to track magnetic field strengths and complexity, a valuable input for flare forecasting.

3.2 Automated Detection of CMEs

The visual detection of CMEs in the flood of incoming LASCO data is a labour-intensive task. Until today it is essentially the human eye that detects a CME occurrence and a scientist that collects all the CME parameters. An automated detection system called “Computer Aided CME Tracking (CACTus) has been developed for the LASCO images (Berghmans et al., 2002). The software detects bright ridges in [height, time] maps using the Hough transform and creates a list of events with principle angle, angular width and velocity estimation for each CME. In contrast to lists assembled by human operators, these CME detections by software can be faster and possibly also more objective. The first version CACTus has been evaluated and it obtained a success rate of about 75%. This number is expected to improve in later versions. The software also detected some CMEs that were not reported in the official human created catalogs.

3.3 Solar Wind Shockspotter

The CELIAS/MTOF/PM instrument on SOHO measures the solar wind speed, density and temperature. The group at the University of Maryland recently implemented a "Shockspotter" program to identify interplanetary shocks in near-real time using proton monitor data. The program is based on semi-empirical algorithms using only solar wind proton data (since no magnetometer data is available on SOHO). Shock candidates are classified into 4 distinct zones, with confidence levels ranging from about 40% to 99%. Results have been used to study the frequency distribution of interplanetary shocks over the solar cycle.

The Shockspotter program is now part of the proton monitor real time data page at http://umtof.umd.edu/pm. The program can alert users (via eMail, upon request) whenever a shock front passes the SOHO spacecraft approximately 30-60 minutes prior to the arrival at Earth. A catalog

---

[*] *A complete list of all detected CMEs with LASCO can be found at: http://lasco-www.nrl.navy.mil/cmelist.html*

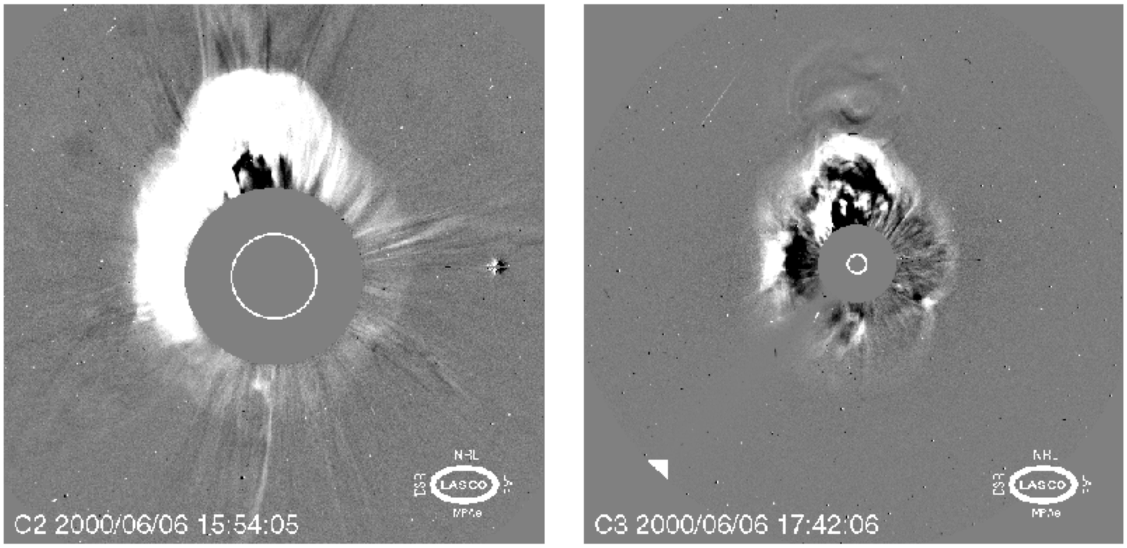

Figure 2. Example of a full halo CME observed by LASCO C2 (left panel) and C3 (right panel) coronagraphs. The field of view of the images are 2-6 and 3.5-30 solar radii

of interplanetary shocks is also maintained at http://umtof.umd.edu/pm/figs.html . The Maryland CELIAS group has also developed Web pages that show the solar energetic particle flux deduced from proton monitor background levels (http://umtof.umd.edu/pm/flare/) and the solar soft X-ray flux from SEM measurements (http://umtof.umd.edu/sem/).

4. SPACE WEATHER EFFECTS ON SOHO

SOHO is designed to withstand the effects of the varying flux of high energy particles encountered in its L1 Halo orbit. These effects can be separated at least into three classes. First we will discuss the effects on the spacecraft (service module and solar panels) and then the effects on the different scientific instruments. A brief summary of efforts to prevent interruptions to the daily operation of the spacecraft is also discussed.

4.1 Effects on the Service Module

4.1.1 Radiation Hazards

During its lifetime the spacecraft components receive an integrated radiation dose that degrade their performance and can cause the following failures:

a) Solar Arrays

The only permanent effect so far is the degradation of the solar arrays due to high energetic protons from solar eruptions. This degradation is due to "displacement damage": energetic particles interact with the solar cell lattice producing defects which enhance electron and hole recombination thus reducing the solar cell's output voltage and current. The actual degradation of the solar array is given in Figure 3. The degradation due to proton events is evident with significant drops during the July 14, 2000 and November 4 & 23, 2001 events. The degradation after 80 months in space is 13.8%. This is an annual average degradation of 2.01%, well within the 4% per year requirement. SOHO can operate down to 70% sensitivity without taking any energy saving action.

b) Sensitivity of the Fine Pointing Sun Sensor

The Fine Pointing Sun Sensor (FPSS), together with the Star Sensor Unit (SSU), is part of SOHOs Attitude and Orbit Control System (AOCS). Similar to the solar array, the FPSS sensitivity is gradually decreasing due to the impinging radiation over several years. The present performance is still sufficient, but in the long run, we might eventually require a new calibration of the output level of the FPSS. This is a simple on-board parameter change.

4.1.2 Radiation Induced Background

Radiation impinging on detectors or associated electronics can produce an increase of the background noise. The Star Sensor Unit consist of an optical system with thermal sensors for calibration of the focal length of the optics and a CCD detector (377 x 283 pixels), mounted on a Peltier cooler with thermal control for the CCD temperature (– 40°C) and for the electronics of the detector drivers and data pre-processing. The background noise of the Star Sensor Unit so far is very stable since the beginning of the mission.

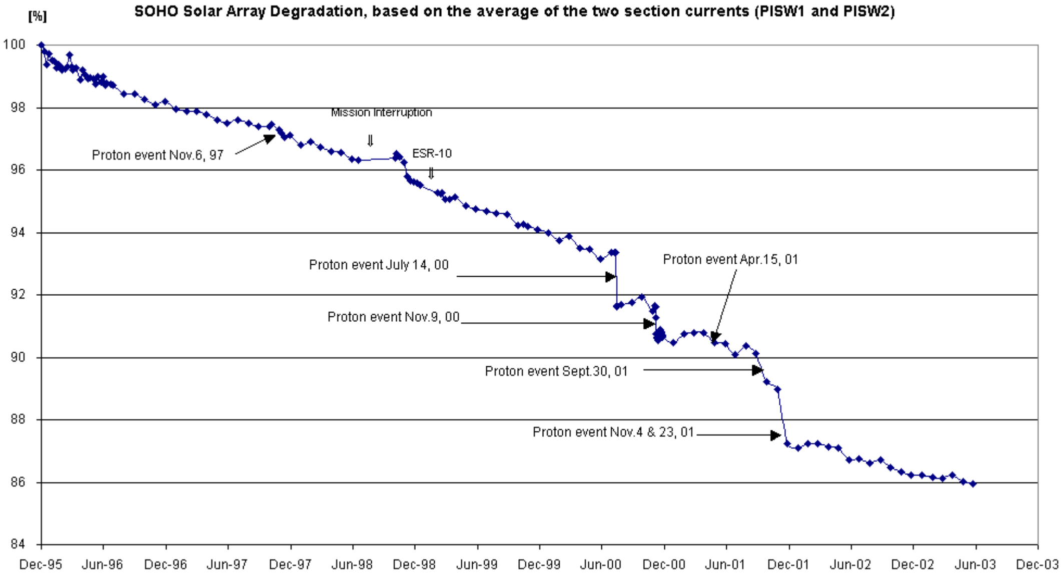

Figure 3. SOHO solar array degradation since the launch in 1995. The drop in sensitivity due to individual proton events is evident.

4.1.3 Single Event Upsets (SEUs)

Cosmic rays or heavy ion impact can provoke single event upsets, which may disrupt the operation of sensitive electronics.

a) Electronic units self switch-off

A fair number of self switch-off events occurred, which are attributed to Single Event Upsets (SEUs). Three of them caused transitions to the spacecraft safe mode (Emergency Sun Reacquisition – ESR), causing major disruptions of science operations. Five times the battery discharge regulators switched themselves off and there were 7 occurrences where instrument boxes were switched off or required rebooting. Many of the self switch-offs are probably caused by false triggering of internal protection circuits, which are designed to protect against over-voltage or over-current. In all cases, no permanent damage occurred and the systems could be re-activated successfully.

b) Solid State Recorder

A major temporary radiation effect is the SEUs in the Solid State Recorder (SSR), resulting in bit flips in the memory. The EDAC (Error Detection And Correction) detects and corrects these single errors (in the same word). Double errors are detected but not corrected.

Single errors are very common for the2 Gbit SSR memory:

- At solar min: 1 SEUs/ min
- At solar max: 0.5 SEUs/min
- During proton events: up to 76 SUEs/min (July 14, 2000 event)

So far there has been only 1 double error since launch, which was corrected as soon as the effected memory location was overwritten with new data. A plot of the SEUs/minute/2 GB over the entire mission is given in Figure 4.

c) Star Sensor Unit

Another temporary radiation effect is observed on the Star Sensor Unit (SSU). When particles hit the CCD (Charge Coupled Device) of the SSU, they generate electrons, which charge up the pixels just like the regular photons, producing bright star-like signatures.

The SOHO star tracker tracks five stars in small tracking windows. If a particle hits the tracking window it can result in a wrong assessment of the tracked star's barycenter and/or magnitude.

The SSU interprets this as a movement of the star it was tracking thus providing wrong information to the attitude control software, resulting in turn in wrongful attitude correction orders to the wheels. Furthermore, the Star Tracker itself is moving its tracking window to the new wrong barycenter, and sometimes loses the true star in doing so.

During the first three years the star tracker had lost the guide star 54 times. Most of these resulted in loss of nominal attitude (fall back into Roll Maneuver Weels mode/gyro mode), with the consequence of reduced science during the special operation to recover to nominal configuration.

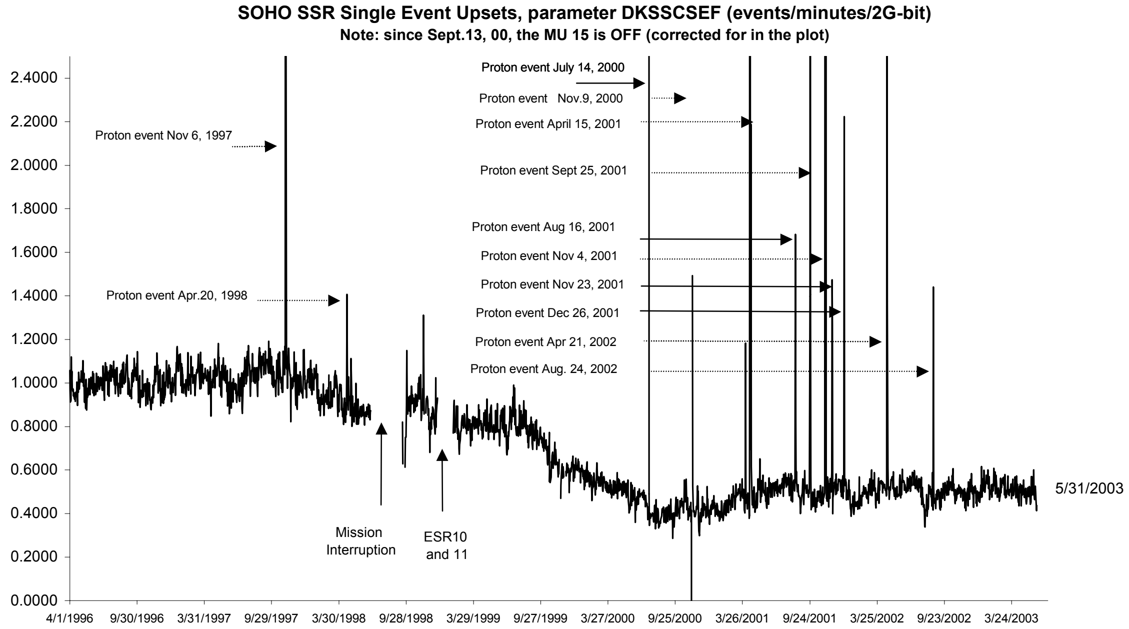

Figure 4. Number of SEU's per minute per 2GB over the entire mission. The solar cycle effect can be clealry seen with more SEU's during solar minimum (weaker solar magnetic field). Overlayed are the proton events during the SOHO mission.

4.1.4 Improvements to Onboard Software

The onboard software was designed to be upgraded and a series of improvements have taken place throughout the mission. Two improvements to increase the robustness to SEUs have been implemented:

4.1.4.1 Star tracker and AOCS software changes

The star tracker's internal software was modified:

- to filter out transient changes in the star barycenter (Position Jump Filter).
- to filter out transient changes in the star's magnitude

The result is that for both transient changes no false event report is sent to the AOCS software.

The AOCS overall task is to provide the spacecraft with the requisite pointing performance during the various spacecraft activities. The AOCS software was modified to delay the effect of false event reports of the SSU to the attitude control computer (Staircase Filter). This filter was first implemented as a patch, but was later included in the “gyroless” software.

4.1.4.2 Automatic "star swap" capability

An automatic "star swap" capability was added to the attitude control computer gyroless software. Before 1998, the control mode was automatically changed from Normal Mode to Roll Maneuver Wheels mode, where the roll control was switched from the star tracker to the gyros, when the guide star was lost or simply flagged invalid due to a SEU. We no longer have gyros for backup, but the new software can now automatically use one of the 4 other stars as new guide star. Thanks to this, SOHO was able to remain in normal mode during the Bastille Day (July 14, 2000; 3 star swaps) and the Nov 9, 2000 event (also 3 star swaps). There have been 11 star swaps in all, since October 1999. Since the new gyroless software with the star swap feature was uploaded, we had not a single loss of nominal attitude (i.e. fall back into the new gyroless Coarse Roll Pointing mode). SEUs can still cause the stars to be flagged "invalid" for a while, but they have always returned to valid on their own. With these new upgrades SOHO is now extremely stable.

4.2 Effects on the Scientific Instruments and Operations

As with spacecraft electronics and detectors, several instruments are also subject to effects from energetic particle events. For some *in situ* sensor instruments, the particles are the main subject matter; for some, the particles are mostly a nuisance causing image degradation, but some instruments have health and safety concerns, due to e.g. high voltages on their detectors, the potential for arcing and permanent damage.

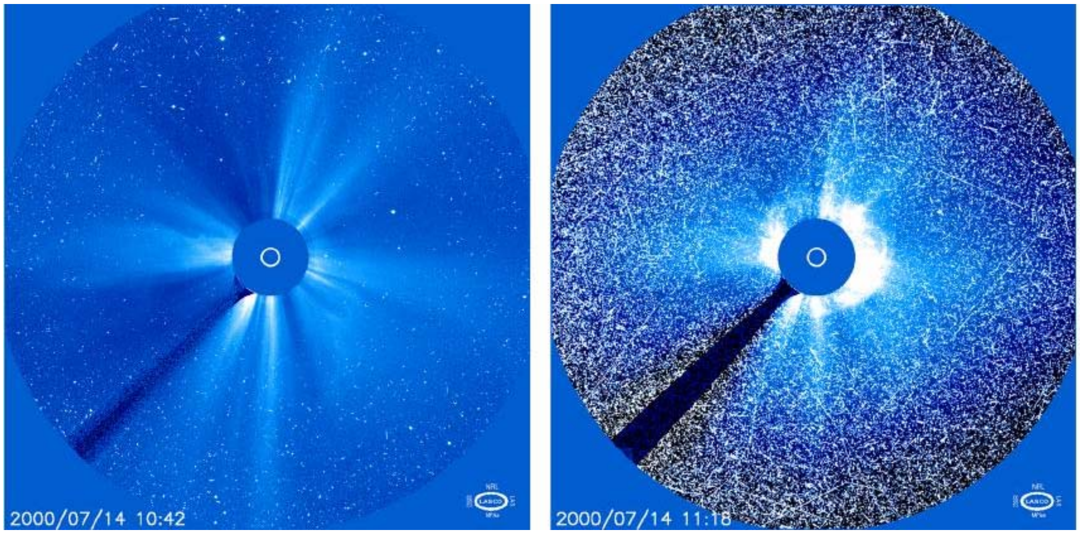

Figure 5. Images taken by the LASCO C3 coronagraph during the July 2000 solar energetic particle event showing severe effects on the detector from radiation background. Note that even though the images appear to be totally swamped during a proton storm, we are scaling the images to show the subtle coronal changes so that the particles are enhanced. They really don't saturate the detectors.

4.2.1 Image Degradation

As can be seen in Figures 5, 6, and 7, the image degradation experienced during energetic particle evens can be quite severe. Not only does the (relatively short-lived) degradation render images nearly useless for scientific analysis and space weather purposes – they also cause them to be much less compressible by the on-board software, in the case of EIT and LASCO. With a limited amount of telemetry and on-board storage, this results in the instrument getting "backed up", with a shifting of scheduled observations to a later time. While not necessarily critical under regular circumstances, certain joint observing programs rely on a closely coordinated timeline between a number of instruments both on board SOHO and on other spacecraft, as well as ground based observations. This can only be corrected by intervention from the ground, using near-real-time (NRT) commanding to flush queues, skip observations, or upload new plans.

4.2.2 Health and Safety Effects

With several types of instruments operating detectors that have high voltage "image intensifiers" of different types, energetic particle showers are not purely an inconvenience. Although no incident has yet damaged any of the SOHO instruments, precautions have been put in place to ensure that the likelihood of damage is being kept as low as possible. Since, in general, the image-intensified instruments' data during particle events are not very useful anyhow, the loss of science data is not of concern; health and safety takes priority for those that feel a "better safe than sorry" approach is appropriate. The instruments that do take precautions of various kinds are: Coronal Diagnostic Spectrometer - CDS (continuous detector readouts to prevent charge build-up), Ultraviolet Coronagraph Spectrometer - UVCS and Solar Ultraviolet Measurements of Emitted Radiation - SUMER (high voltages turned down).

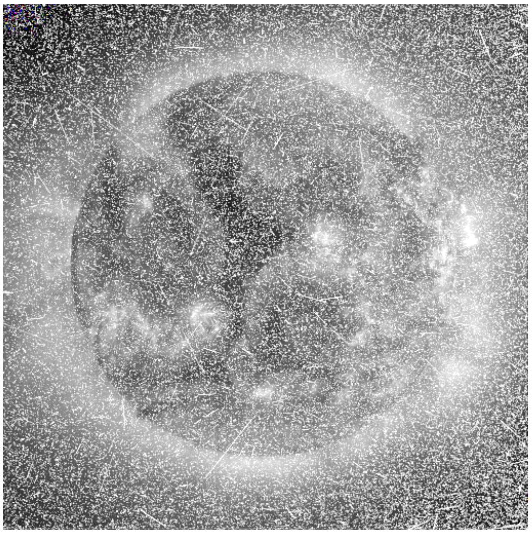

Figure 6. The SOHO Extreme Ultraviolet Imaging Telescope (EIT) observing during a proton event.

4.2.3 Operational Implications

The main operational "warning system" is the spacecraft solid state recorder. Since the SSR SEU counter is being monitored on the ground while the spacecraft is in contact (to prevent the SEU counter from overflowing), the impacts to normal operations are minimal when there is no particle event. If the

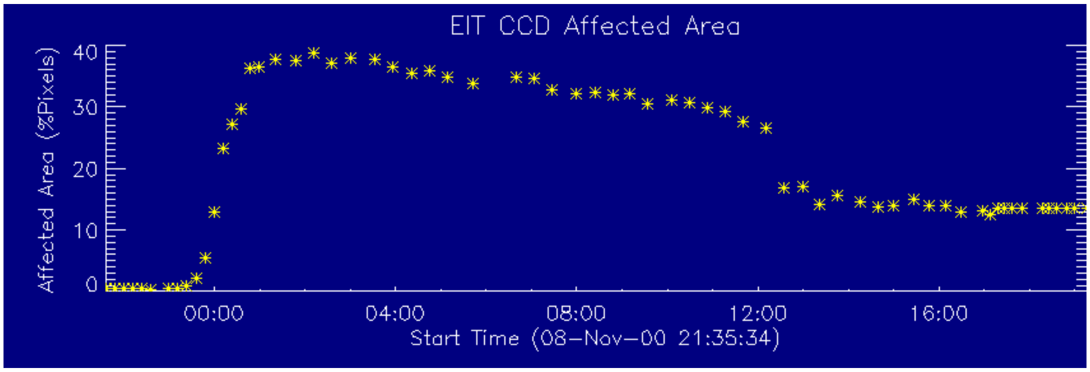

Figure 7. During a strong proton storm about 40% of the EIT detector is affected. The effect of the protons can be seen for a few.

SEU counter needs to be reset more often than once per hour, the Science Operations Coordinators are contacted, alerting instrument teams about the situation according to their own criteria.

For times when the spacecraft is not in contact, the warning system is based on NOAA GOES data from the web. Of course, with no spacecraft contact, nothing can be done about the instruments, so the status is only checked some time in advance of station passes with commanding ability. In addition, a 24/7 system based on automatic paging of the SOCs is in place, using NOAA GOES data from the web.

4.2.4 Long-term Effects

No serious long-term adverse effects have yet been noted, although the high energy particle environment does contribute to the gradual degradation of instruments. In particular, contaminant "doping" of refractive optics changes the absorption coefficients (impacting the optics temperatures), and the indices of refraction (focus changes). In addition, parts of the gradual sensitivity losses experience by many instruments can be attributed to contamination of detector electronics.

5. MISSION STATUS AND FUTURE PLANS

Although long past the design lifetime of 2 years, SOHO is doing remarkably well. Fuel reserves of 123 kg should last 10 more years according to conservative estimates, and the solar array degradation is at only 10%, with a remaining margin of 25% before conservation measures must be applied. The gradual degradation of instruments and multi-layer insulation due to EUV exposure and high-energy particles is as expected, and not a cause of concern. Barring unexpected events, there seems to be no technical reason why SOHO and its instruments should not be able to complete of a full solar cycle. With several years until heirs to the throne can be expected, we hope that SOHO will continue its hegemony in the field of solar and heliospheric observations for years to come.

6. ACKNOWLEGEMENTS

We would like to thank Christopher Balch (SEC) and Fred Ipavich (Univ. of Maryland) for very useful input and comments to this paper.

7. REFERENCES

Berghmans, D., Clette, F., Cugnon, P., Gabryl, J.-R., Hochedez, J.-F., Van der Linden, R., A.M., Verwichte, E., 2002, JASPT, 64, 757

Domingo, V., Fleck, B., and Poland, A.I. 1995, Solar Physics, 162, 1.

Howard, R. A., Michels, D. J., Sheeley, N. R., Jr., and Koomen, M. J. ApJL, 263, 101.

St.Cyr, C., Howard, R. A., Sheeley, N. R. 2000, J. of Geophys. Res., 105, 185.

Zhang, J., Dere, K. P., Howard, R. A., Bothmer, V. 2002, ApJ, 582, 520