CHANDRA
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Date: May 14, 2024
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To: Chandra Operations Team
Subject: Chandra Radiation Event and Shutdown in March 2024
Cc: MSFC Project Science, CXC Director's Office
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1 Abstract

This memo discusses the thought process that the operations team, especially the ACIS operations team, used during a very high radiation event between March 22-24, 2024. *Chandra* was shut down via an automatic trigger of SCS-107 via the ACIS *txings* algorithm. The key decision points to continue or suspend science operations are reviewed, and the details of the storm are presented.

During this storm, the accumulated attenuated ACE P3 fluence was approximately 2.35×10^8. Thanks to the automatic shutdown, ACIS avoided accumulating another $\sim 3.02 \times 10^9$ of P3 fluence. The agreed annual budget for this quantity is 2.0×10^{10}.

2 Introduction

During the weekend of March 23-24, 2024, *Chandra* experienced a radiation storm which resulted in the autonomous shutdown of the spacecraft via an ACIS txings trigger of SCS-107 to protect the ACIS instrument from the damaging soft solar wind protons that increase CTI. Solar activity is high this year as we approach solar maximum.

At this point in the mission, the HRC Anti-Coincidence shield rate, which had been the radiation monitor for some time, was no longer available. The ACIS txings rates serve as the only available way to trigger autonomous shutdowns due to high radiation levels. In this storm, the txings rates reached their trigger levels right before the peak of the proton rates in nearly all channels, averting a signficant amount of radiation damage to the ACIS CCDs from soft ($\sim$100 keV) proton fluence.

This memo discusses the properties of the storm, the radiation received in terms of the single-orbit and annual budgets, the differences between various radiation measurements, and the response.

3 Mar 23-26 2024 Detailed Timeline

Note: all times are in UTC and may be approximate.

- 2024:083 **Saturday March 23, 2024**
- 2024:083:00:00:00 The MAR1824B load is in progress.
- 2024:083:01:33:00 Earth-orbiting satellites detect an X1.1-class solar flare.
- 2024:083:04:00:00 GOES proton channels and the HRC Proxy begin rising sharply, and will continue to rise for the next 14 hours, up to a value of $\sim 3 \times 10^3$.
- 2024:083:10:00:01 **Comm** begins (60 min).
- 2024:083:10:18:58 Time of RADMON enable from the MAR1824B loads. ACE P3 rates are ~100 and rising slowly.
- 2024:083:18:30:01 **Comm** begins (60 min); ACIS TXings has not autonomously shut down the spacecraft. The HRC Proxy begins a sharp decline for the next hour, but levels off at a still high value of $\sim 10^3$ for the next ~16 hours. ACE P3 at this time is $\sim 10^3$ and continues to slowly increase.
- 2024:084 **Sunday March 24, 2024**
- 2024:084:10:30:00 Space weather alerts go out indicating a CME is approaching Earth. ACE P3 rate is $\sim 6 \times 10^3$ and climbing.
- 2024:084:11:34:34 SCS-107 runs due to a txings trigger, out of comm.
- 2024:084:12:00:00 The ACE P3 rate rises rapidly over a period of two, from $\sim 10^4$ to $\sim 3 \times 10^5$.
- 2024:084:14:30:00 A CME hits Earth's magnetic field, producing a G4-class storm.
- 2024:084:17:15:00 The ACIS Ops on-duty scientist calls a telecon to discuss the radiation situation. During this telecon, the decision is made to shut down manually.
- 2024:084:17:55:00 **Comm** begins (60 min) with a call-up 15 minutes early; the Chandra operations team discovers that SCS-107 was triggered since the last comm.
- 2024:085 **Monday March 25, 2024**
- 2024:085:01:53:41 First command from the MAR2524A loads, which are now vehicle-only.
- 2024:085:03:00:00 **Comm** begins (60 min).

- 2024:085:11:20:00 **Comm** begins (60 min).
- 2024:085:22:45:00 **Comm** begins (50 min).
- 2024:086 **Tuesday March 26, 2024**
- 2024:086:04:00:00 First command of the MAR2624A replan loads.

4 Discussion

A couple of sunspot regions had been active in the few days leading up to the weekend of March 23-24. In the very early hours (UTC) of March 23, these two groups produced solar flares at nearly the same time. For the rest of the day, ACE P3 rates steadily increased, climbing to a value of $\sim 10^3$ at $\sim$19:00 UTC. In this same time period, the HRC proxy rose dramatically, above the HRC Shield trigger level of 245, settling at a value of $\sim 10^3$ for the next 18 hours. There was a comm at this time, but given the relatively low ACE P3 rates, no action was taken, and the txings algorithm had not shut down the spacecraft.

Over the course of late March 23 and the first half of March 24 (UTC), ACE P3 rose slowly. However, this determination can only be made after the fact, due to the fact that most of this period was characterized by spuriously high values in the ACE data that appeared as sudden, discontinuous jumps (see Figure 2). The ACIS Ops team had to rely on interpolation between the ACE P3 data points that were deemed physical to make a reliable estimate of the fluence that was accumulating. At a few decision points during the day, no action was recommended, given the low accumulated ACE P3 fluence and its slow rise, as determined by the "good" data points.

At 2024:084:10:30:00 UTC (6:30 am EDT, Sunday March 24), space weather alerts went out, indicating a CME was approaching earth. An hour and a half later, ACE P3 rates began to increase rapidly, and continued to increase until reaching a maximum of $\sim 3 \times 10^5$ at 2024:084:14:00:00 UTC (10:00 am EDT). Some discussion between the ACIS Ops team members occurred over email during this time, and it was agreed that it was time to call for a shutdown at the next real-time comm, scheduled for 2024:084:18:10:00 (2:10 pm EDT). Despite the noisy ACE data, it was estimated that at this point we had accumulated roughly $\sim 2 \times 10^9$ of P3 fluence.

The telecon occurred at 2024:084:17:15:00 (1:15 pm EDT). There was no disagreement at this telecon that a manual shutdown was necessary. Contact with the spacecraft was achieved 15 minutes early at 2024:084:17:55:00 (1:55 pm EDT), and it was discovered that SCS-107 had already been triggered by the txings algorithm at 2024:084:11:34:34, before the sharp rise in ACE P3 (Figure 4). The return to science was planned to take place immediately after the next radzone exit. In the meantime, the MAR2524A load products, which were already approved, had their vehicle-only portion uplinked.

In the end, the total accumulated fluence for the orbit, computed from the ACE dump data, was 2.35×10^8. The total ACE P3 fluence that would have been accumulated during the entire science orbit is 4.55×10^9 (accounting for an 8 ks HRC observation when ACIS would have been out of the focal plane). Given the decision to manually execute SCS-107 at the comm The ACIS txings trigger of SCS-107 prevented the accumulation of another $\sim 3.02 \times 10^9$ of P3 fluence, the vast majority of which would have accumulated in the $\sim$6 hours after the SCS-107 actually occurred.

The HRC Anti-Co Shield is no longer operational for radiation monitoring. However, we can check the HRC Shield GOES Proxy to determine if there would have been an autonomous shutdown had it been available. The HRC Proxy went above its trigger level of 245 at approximately 2024:083:11:02. If the HRC Anti-Co Shield were operational, an autonomous shutdown may have occurred much earlier. (Figure 5).

5 Data plots for the March 2024 storm

In Figure 1, we have plotted the 5-minute averaged ACE P3 flux rate, in the usual units, which are protons s^{-1} cm^{-2} sr^{-1} MeV^{-1}, throughout the March storm. Also marked are radiation belt passages, the time of autonomous SCS-107 execution, the approximate time of the planned manual SCS-107 execution, the time of the start of the MAR2524A vehicle-only loads, and the time of the nominal RADMON disable from the same loads (the same times are marked in the rest of the radiation vs. time plots).

Figure 2 shows the ACE P3 flux during the storm using the real-time data. The real-time data (blue) exhibits a large number of unphysical spikes which, if taken to be real, would have indicated a much higher fluence accumulation rate. These values were ignored. The orange curve shows the interpolated fluence accumulation rate, made assuming that points below a certain threshold were unphysical. Comparison of this plot with Figure 1 shows that the interpolated flux was very consistent with the actual data obtained later from the ground-processed ACE dump data.

Figure 3 shows the flux from four ACE proton channels (P1, P3, P5, and P7) during the storm. Though only P3 is our proxy for damage to the ACIS CCDs, the other channels can serve as informative diagnostics. Of particular interest is the behavior of the channels P3, P5, and P7 beginning at approximately 2024:083:15:00. After this time and until the sharp increase in ACE P3 after the autonomous shutdown, the flux in these channels is relatively flat and hard, which can often point to significant P3 flux occurring downstream.

In Figure 4, we present the ACIS threshold crossings as a function of time for the days of the storm. The FI rates never reached their trip levels during the orbit. The BI rates did reach the trip levels occasionally during OBSIDs 29014 and 29033, but they were not monotonic and so the txings algorithm never tripped. Figure **??** shows a close-up of the txings rates on DOY 308-309.

Finally, Figure 5 shows the HRC Shield Proxy during the storm. As already noted, the HRC Anti-Coincidence Shield rates are no longer available for radiation monitoring, but had they been, they would have triggered SCS-107 shortly after the beginning of the

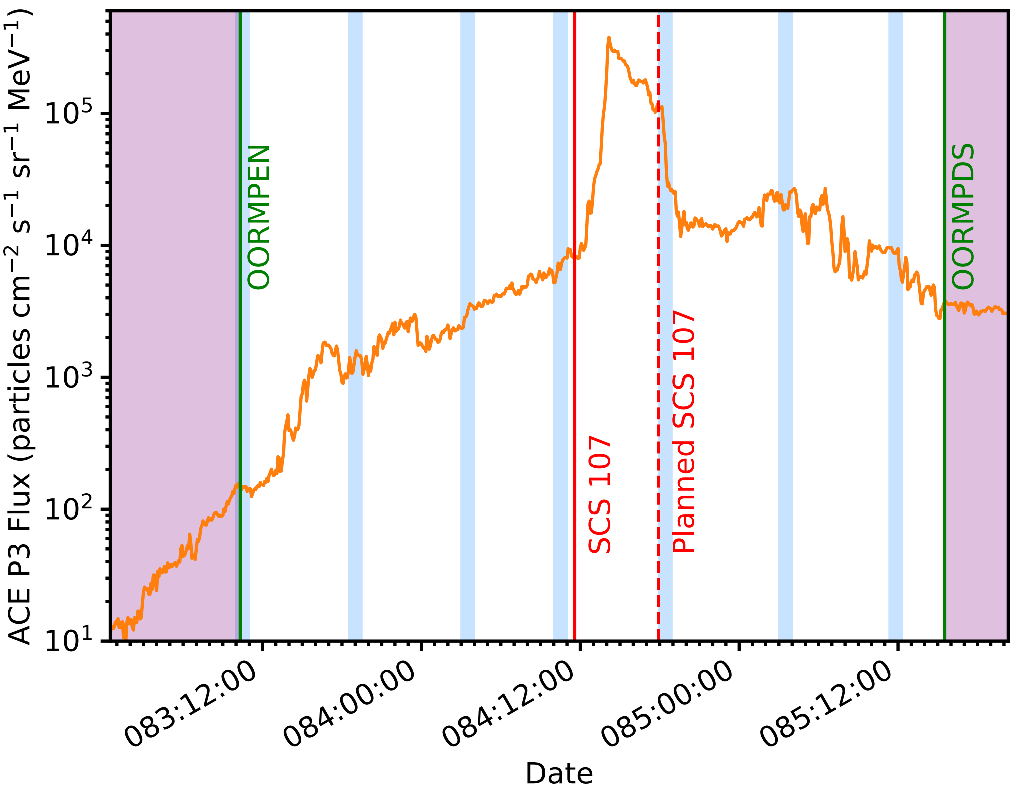

Figure 1: A plot of the ACE P3 flux during the March 2024 storm. Purple shaded regions indicate the radzone passages, during which HRC is in focus. Fluence is integrated when ACIS is in focus, and is counted from radzone exit. Blue shaded regions mark scheduled DSN communications.

science orbit.

6 Lessons Learned

- ACE data dropouts and spikes can make it difficult to determine the true fluence accumulation rate. The ACIS Ops team had to rely on interpolation between the "good" data points to make a reliable estimate of the fluence that was accumulating. These anomalous values typically only appear in the real-time data and are not present in the data processed on the ground.
- Many storms exhibit a hard and flat spectrum across the ACE proton channels before a steep rise in ACE P3, and this storm did indeed have such a feature.

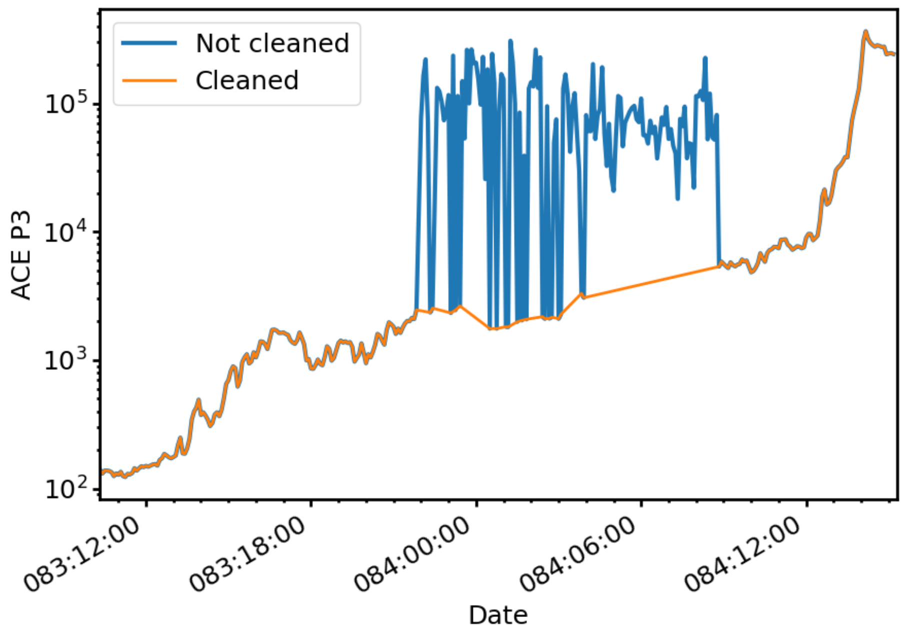

Figure 2: A plot of the ACE P3 flux during the March 2024 storm made using real-time data, showing the uncorrected data (blue) and the points that were deemed "good" (orange), which were interpolated between to estimate a likely fluence value. Shaded regions and vertical lines have the same meaning as in Figure 1.

- The HRC proxy was above its trigger level long before the time of the autonomous shutdown–indicating that the HRC Anti-Co Shield would have triggered an autonomous shutdown much earlier had it been operational. There is currently no similar proxy for the ACIS txings rates which could potentially have predicted the autonomous shutdown. This episode motivates the need to produce such a proxy.

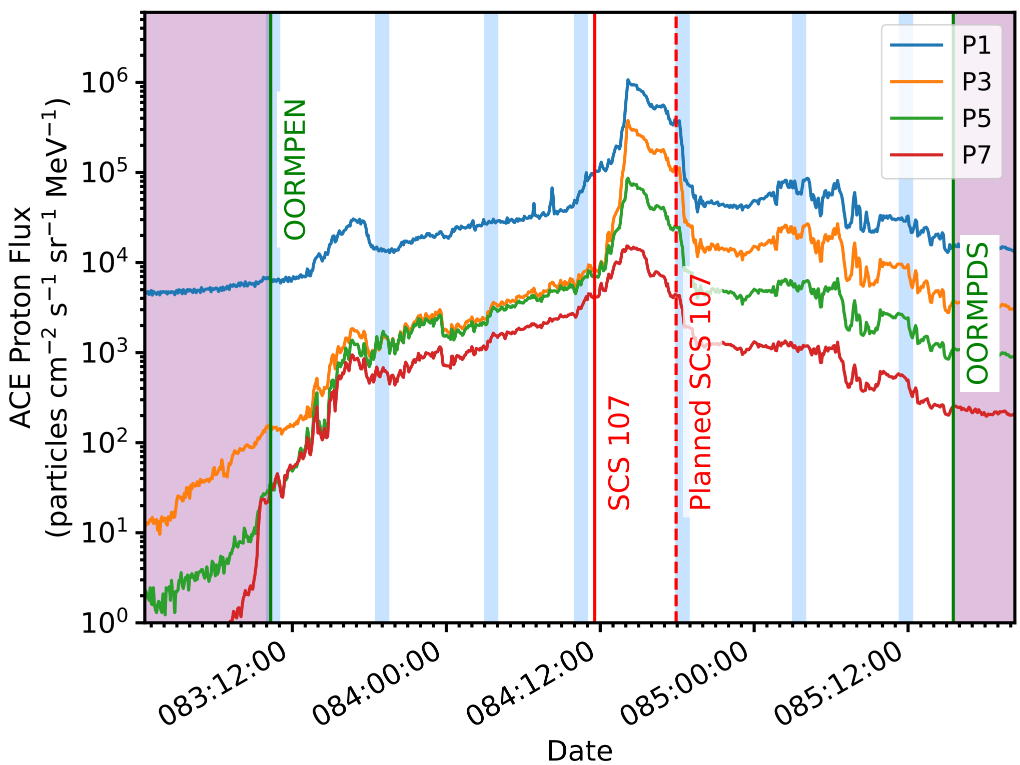

Figure 3: A plot of the flux from the four ACE channels P1, P3, P5, and P7 during the March storm. Shaded regions and vertical lines have the same meaning as in Figure 1.

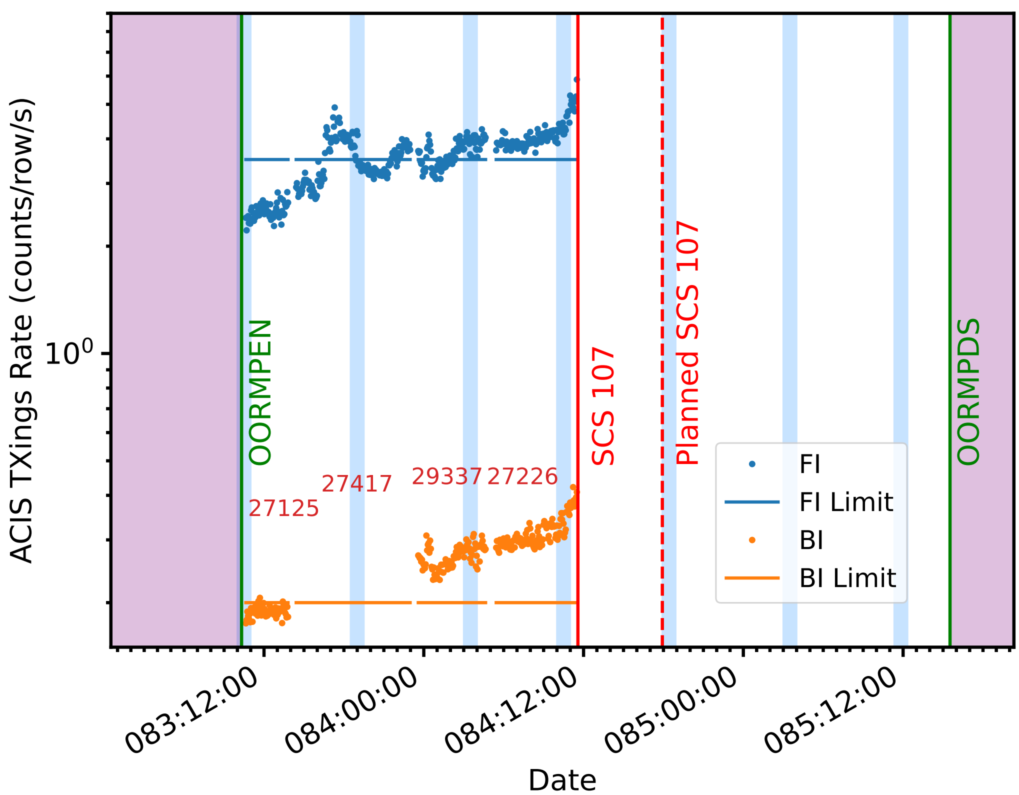

Figure 4: A plot of the txings data during the March 2024 storm. Blue is for FI chips, orange is for BI. The horizontal lines are the increasing values trip thresholds for each type of chip. Shaded regions and vertical lines have the same meaning as in Figure 1.

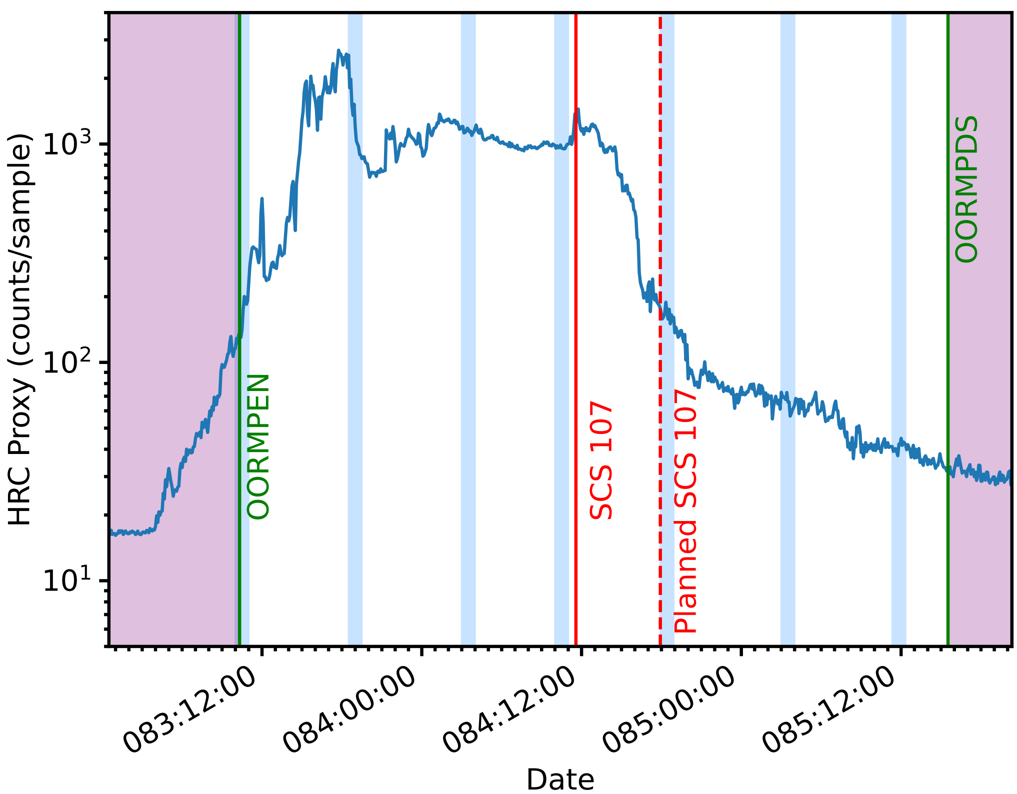

Figure 5: The HRC Shield proxy during the storm. Shaded regions and vertical lines have the same meaning as in Figure 1. The HRC proxy exceeded its trigger value of 245 shortly after entry into the science orbit, and remained at a very high level until the shutdown occurred.

7 Resources

The archive of ACE data stored in ASCII tables at `https://sohoftp.nascom.nasa.gov/sdb/goes/ace/daily/` has gaps that are not back-filled; the full dataset can however be found in the "ACE Browse" archive:

`ftp://mussel.srl.caltech.edu/pub/ace/browse/`

The data are in HDF4 format, which can be converted to HDF5 data by use of a program `h4toh5` which I downloaded from `https://www.hdfeos.org/software/h4toh5.php`. A Python script, `get_ace.py`, which downloads the data and uses `h4toh5` to convert it is available on the HEAD LAN in `/data/acis/ace`. Instructions for downloading the data using this script and extracting the ACE proton channels are given in `/data/acis/ace/README_browse.md`.

The HRC Shield Proxy and GOES proton data are stored in HDF5 format here:

`/proj/sot/ska/data/arc/hrc_shield.h5`.

Thanks to Peter Ford for providing the ACIS txings data.