CHANDRA
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Date: January 29, 2024
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To: Chandra Operations Team
Subject: Chandra Radiation Event and Shutdown in November 2023
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 November 3-7, 2023. Chandra was shut down via a manual trigger of SCS-107. The key decision points to continue or suspend science operations are reviewed.

During this storm, the accumulated attenuated ACE P3 fluence was approximately 1.61×10^9. Thanks to the manual shutdown, ACIS avoided accumulating another $\sim 1.77 \times 10^9$ of P3 fluence. The agreed annual budget for this quantity is 2.0×10^{10}. As of November 5th, we have accumulated a summed fluence of about $XX \times 10^9$, or roughly XX% of the annual budget.

2 Introduction

On November 5th, 2023 *Chandra* experienced a radiation storm which required manual triggering of SCS-107 to protect the ACIS instrument from the damaging soft solar wind protons that increase CTI. Solar activity is increasing in 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 serves as the only available way to trigger autonomous shutdowns due to high radiation levels. In this storm, the txings rates occasionally reached their trigger levels, but were never monotonic, and thus despite the high levels of radiation *Chandra* did not shut down autonomously. This is because the proton spectrum of the storm was relatively soft, and the ACIS txings rates (like the HRC shield rate) are most affected by the higher energy particles.

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 Nov 3-7 2023 Detailed Timeline

Note: all times are in UTC and may be approximate. Also, the changeover from Daylight Savings Time to Standard Time occurred on November 5, 2023 at 2:00 am EST (7:00 UTC).

- 2023:307:12:00:00 **Friday November 3, 2023** OCT2823A load is in progress. ACE P3 rates are ∼400 and have been holding steady at this level for several days.
- 2023:307:20:26:29 RADMON disable from the daily loads.
- 2023:308 **Saturday November 4, 2023**
- 2023:308:09:03:48 RADMON enable from the daily loads.
- 2023:308:12:00:00 ACE P3 rates begin climbing above $\sim 2 \times 10^3$.
- 2023:308:21:20:00 The ACIS Ops on-duty scientist notes the increase in ACE P3 at the real-time comm: current value is $\sim 6.5 \times 10^3$.
- 2023:309 **Sunday November 5, 2023**
- 2023:309:02:00:00 ACE P3 rate reaches $\sim 2 \times 10^4$, and remains roughly at this level for ∼7 hours.
- 2023:309:08:31:00 Space weather alerts go out indicating a CME is approaching Earth.
- 2023:309:09:00:00 ACE P3 begins to increase rapidly.
- 2023:309:10:05:04 *Chandra* reaches apogee for the orbit.
- 2023:309:11:50:00 ACE P3 reaches a maximum for the orbit of $\sim 2.83 \times 10^5$.
- 2023:309:11:57:00 Alerts go out to `sot_ace_alert` indicating that an ACE P3 fluence of 4.55×10^8 had been accumulated within a 2-hour period.
- 2023:309:12:05:00 **Comm** begins (60 min); ACIS TXings has not autonomously shut down the spacecraft.
- 2023:309:12:15:00 A decision is made by ACIS Ops to call a telecon to discuss manually shutting down *Chandra* during the current comm. During this telecon, the decision is made to shut down.
- 2023:309:12:16:01 Alerts go out to `sot_ace_alert` indicating that an ACE P3 fluence of 1.03×10^9 had been accumulated since the last RADMON enable.
- 2023:309:12:30:44 SCS-107 runs.

- 2023:309:23:33:43 The vehicle-only segment of the NOV0623A load products begins.
- 2023:310 **Monday November 6, 2023**
- 2023:310:10:50:28 Originally planned time of RADMON disable from the daily loads.
- 2023:311 **Tuesday November 7, 2023**
- 2023:311:04:12:00 First command of the NOV0723A replan loads.

4 Discussion

Predictions that the Sun would be active over the weekend were made the morning of Saturday, November 4. At around midday UTC, ACE P3 rates began to climb slowly. For the rest of the day, ACE P3 rates increased, climbing to a value of $\sim 2 \times 10^4$ at ~2:00 UTC on Sunday November 5, and plateauing at that value for the next ~7 hours.

At 2023:309:08:31:00 UTC (6:31 am EST, Sunday November 5), space weather alerts went out indicating a CME is approaching earth. Roughly 30 minutes later, ACE P3 rates began to increase rapidly, and continued to increase until reaching a maximum of $\sim 2.83 \times 10^5$ at 2023:309:11:50:00 UTC (6:50 am EST). At 2023:309:11:57:00 UTC (6:57 am EST), alerts went out to `sot_ace_alert` indicating that an ACE P3 fluence of 4.55×10^8 had been accumulated within a 2-hour period.

Some discussion between the ACIS Ops team members occurred over email during this time. It was projected that we may hit a fluence of 2×10^9 by the time of the real-time comm at 2023:309:13:15:00 (1:15 pm EST). There were no gratings observations in the rest of the schedule that would have decreased this estimate, and only one short (11 ks) HRC observation, so ACIS would be in the focal plane unprotected for the vast majority of the rest of the orbit. The next real-time comm was scheduled within the hour at 2023:309:12:05:00 (7:05 am EST). When *Chandra* came up at this comm, ACIS was still taking data and the txings algorithm had not shut the spacecraft down. Figure 3 shows the txings rates and the trigger limits for increasing values on the FI and BI chips for the length of the storm. The BI rates were occasionally high and above their limits on DOY 308 but did not trigger, since they were not consistently increasing (Figure 4).

Given that the ACE P3 flux showed no signs of leveling off, only one HRC observation was left in the orbit, and the fact that the next RADMON disable was not for ~23 hours, ACIS ops decided to call for a manual shutdown telecon at 12:15 UTC (7:15 am EST) with the rest of the project. Shortly after the call for the telecon, alerts went out to `sot_ace_alert` indicating that an ACE P3 fluence of 1.03×10^9 had been accumulated since the last RADMON enable.

There was no disagreement at this telecon that a manual shutdown was necessary. Most of the discussion concerned the return to science. Consideration was given to any time-constrained targets in the rest of the OCT2823 schedule and the following NOV0623 schedule. SCS-107 was manually executed at 2023:309:12:30:44.

The return to science was planned to take place immediately after the next radzone exit. In the meantime, the NOV0623 load products, which were already approved, had their vehicle-only portion uplinked. This fact was not mentioned in the original email that went out about the NOV0723 return-to-science load products. Given that a portion of the NOV0623 load was run as vehicle-only, this necessitated a manual edit to the ACIS continuity files to ensure that the spacecraft states were correct for thermal modeling purposes for the return-to-science load review.

In the end, the total accumulated fluence for the orbit, computed from the ACE dump data, was 1.61×10^9, ∼20% higher than the 1.31×10^9 estimated at the time of the shutdown. This is because in real-time the ACE data has dropouts that occur with varying frequency. Filled-out ACE data can be obtained at a later time from the ACE Science Center FTP site (see Section 7 for more information). If we had not shut down, this data indicates that another $\sim 1.77 \times 10^9$ of attenuated fluence would have been accumulated.

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 never went above the trigger limit of 245, and in fact was low (over an order of magnitude lower than the trigger level) and flat throughout the storm (Figure 5).

5 Data plots for the November 2023 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 November storm. Also marked are radiation belt passages, the time of manual SCS-107 execution, the time of the start of the NOV0623 vehicle-only loads, the time of the nominal RADMON disable from the same laods, and the start of the NOV0723 loads (the same times are marked in the rest of the radiation vs. time plots). Rates begin to rise roughly one hour after the RADMON disable, and on average continue to rise for the next ∼23 hours. The ACE P3 rate reaches a maximum of $\sim 2.83 \times 10^5$ at 2023:309:11:50:00 (immediately before SCS 107 execution), and then begins to fall afterward, reaching a mostly level value of $\sim 1 - 2 \times 10^3$ after 24 hours (with an excursion up to $\sim 6 \times 10^3$ between 310:12:00:00 and 311:00:00:00), which persists into the beginning of the NOV0723 replan loads.

Figure 2 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 during the steep rise in the first half of DOY 73. Unlike other storms, during this storm the spectrum of the ACE protons never became very flat and hard (see `https://cxc.harvard.edu/acis/storms` for examples of this), which can often point to

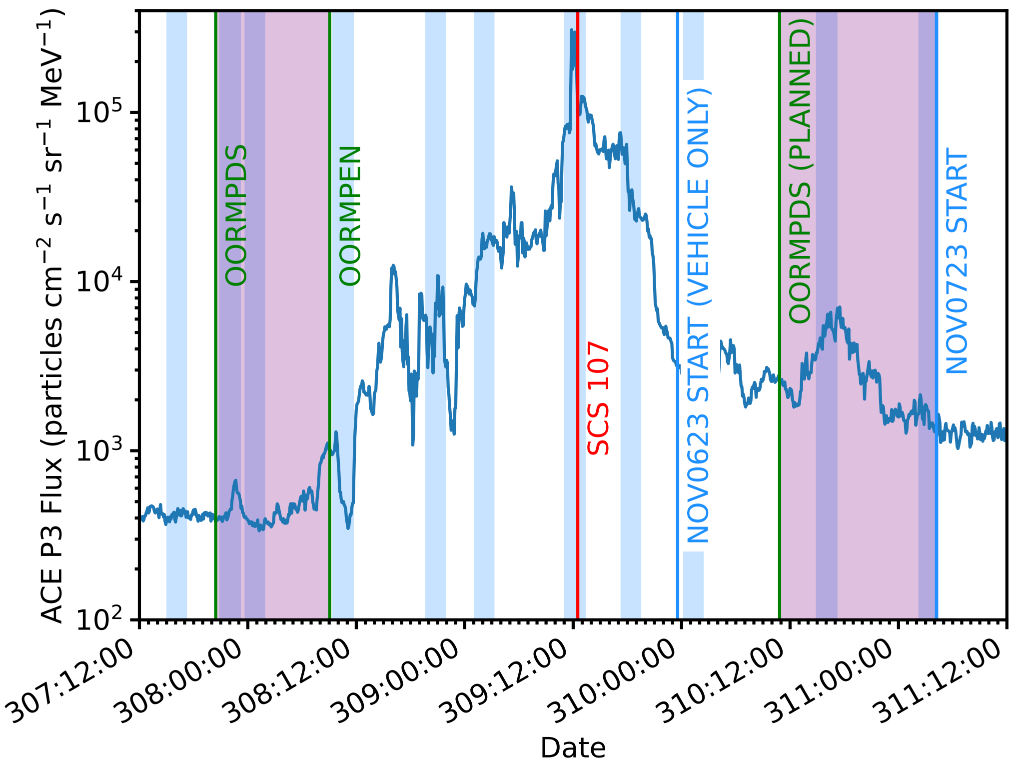

Figure 1: A plot of the ACE P3 flux during the November 2023 storm. Purple shaded regions indicate the radzone passages, during which HRC is in focus. Fluence is integrated when ACIS is in focus, and is counted from radzone exit. Blue shaded regions mark scheduled DSN communications.

significant P3 flux occurring downstream.

In Figure 3, 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 4 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 not have triggered SCS-107, as they were completely flat and low during this storm.

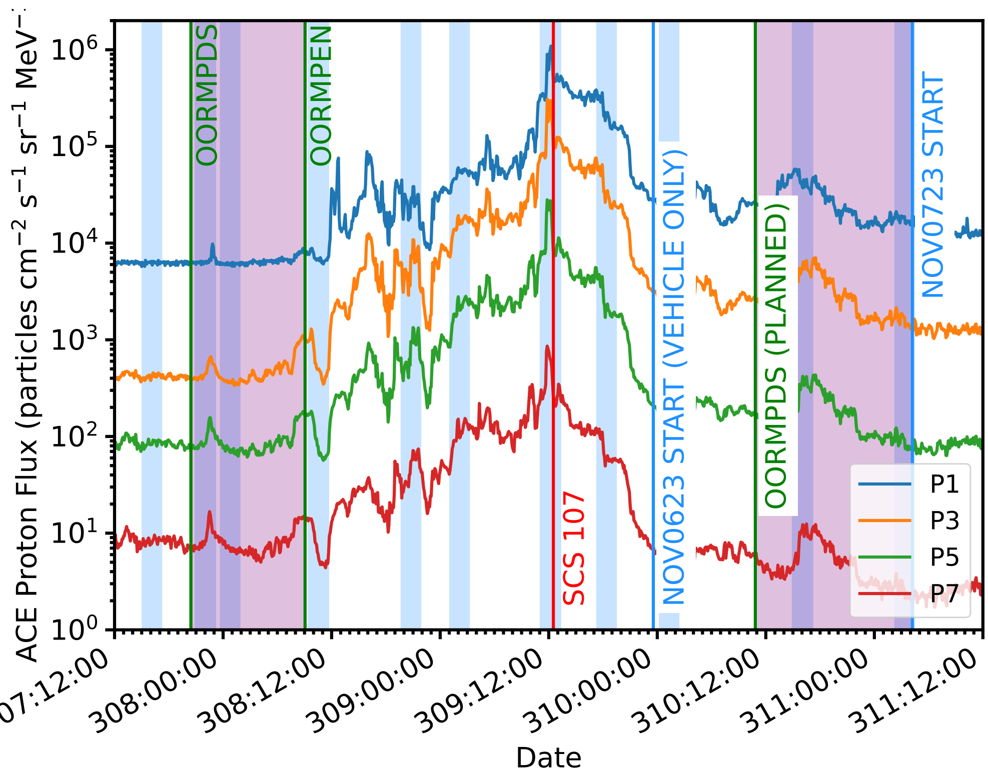

Figure 2: A plot of the flux from the four ACE channels P1, P3, P5, and P7 during the November storm. Shaded regions and vertical lines have the same meaning as in Figure 1.

6 Lessons Learned

- The fluence taken per orbit from the fluence integrator must always be recognized as a lower limit–the real-time ACE data is subject to frequent dropouts that are only backfilled later. In this case, the difference between actual fluence and known fluence at the time was ∼20%.
- The ACIS Ops on-duty scientist who calls the telecon should lead the initial discussion, to ensure that the ACIS Ops position is presented and the discussion focuses on the decision whether or not to call for a shutdown until such a decision is made. Leadership can then be passed to mission planning and the flight directors for the subsequent conversation about the return to science.
- Many storms exhibit a hard and flat spectrum across the ACE proton channels before a steep rise in ACE P3, but this storm did not have such a feature, despite all channels reaching high levels during the peak of the storm. This feature can thus not always

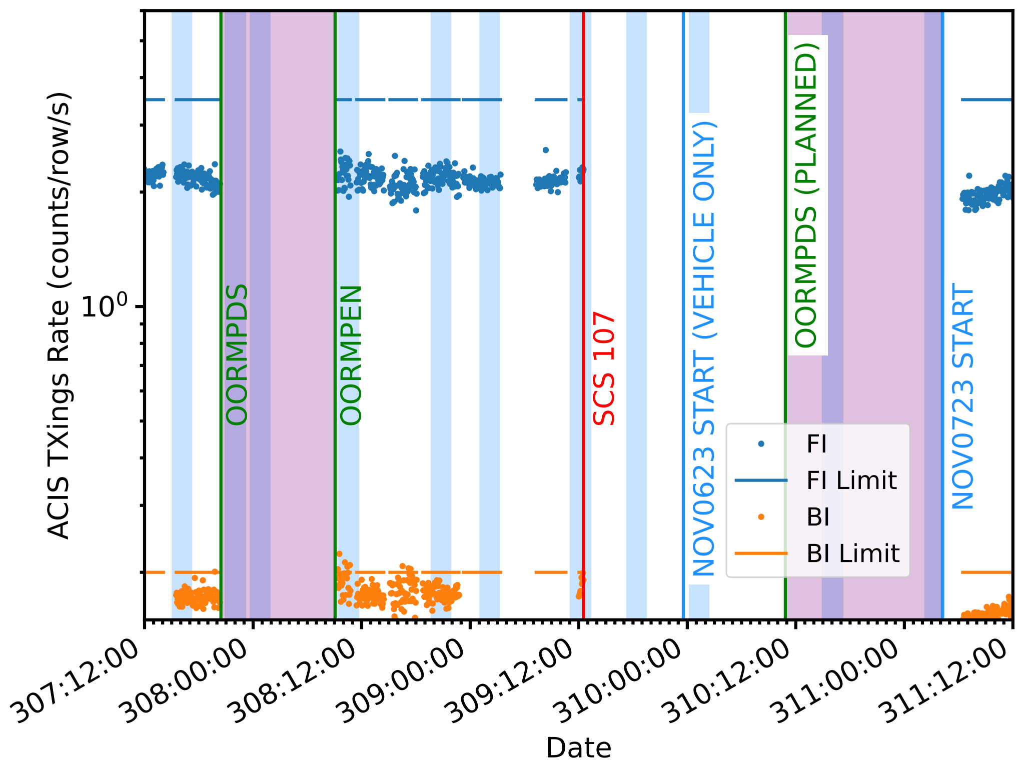

Figure 3: The txings plot for 2023:307-2023:311 (November 3-7). Blue is for FI chips, orange is for BI. The horizontal lines are the increasing values trip thresholds for each type of chip. Shaded regions and vertical lines have the same meaning as in Figure 1. Though the txings values were above the thresholds occasionally during two observations, the algorithm did not trip since the data were not monotonically increasing at these times.

be used to predict that the rates are about to increase rapidly.

- Care should be taken to note the timeline of return-to-science, and if the next week's load has already been approved and if only the vehicle-only portion of that load will be uplinked. This may necessiate manual edits to the ACIS continuity files to ensure that the continuity of spacecraft states is correct for thermal modeling purposes for the return-to-science load review.

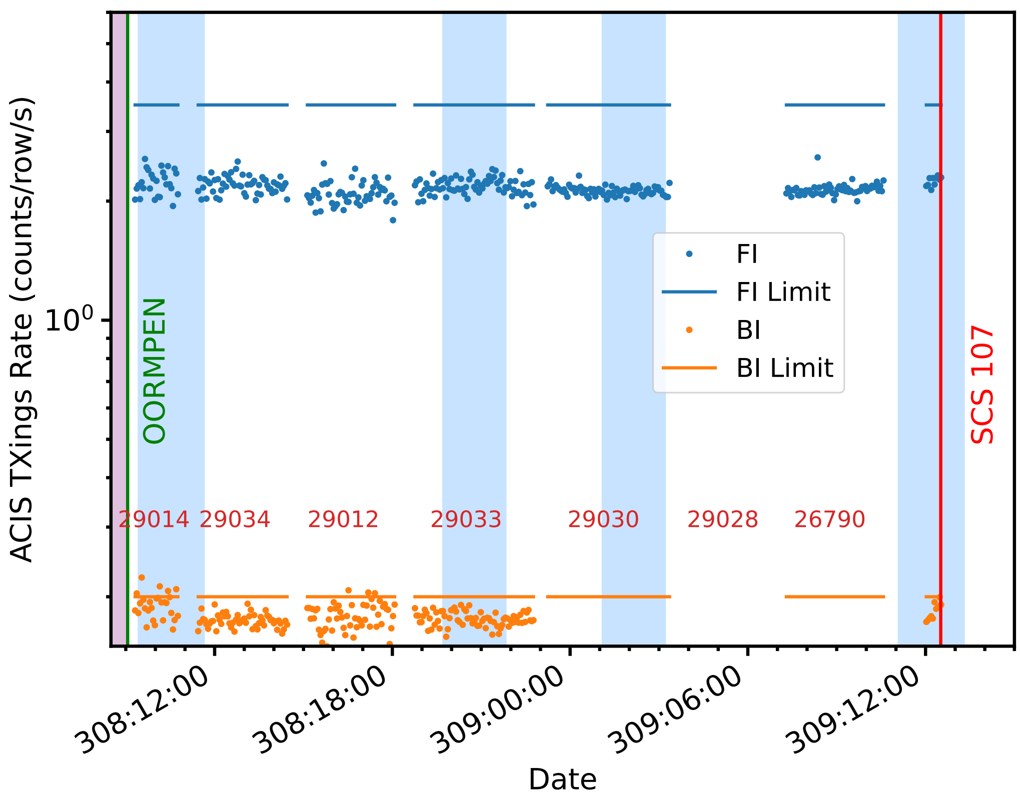

Figure 4: The txings plot for 2023:308-2023:309 (November 4-5). Blue is for FI chips, orange is for BI. The horizontal lines are the increasing values trip thresholds for each type of chip. Individual obsids are labeled. Shaded regions and vertical lines have the same meaning as in Figure 1. Though the txings values were above the thresholds occasionally during two observations, the algorithm did not trip since the data were not monotonically increasing at these times. OBSID 29028 is an HRC-I observation; though txings is running during such observations as a radiation monitor, the values are not currently telemetered and hence are not shown here.

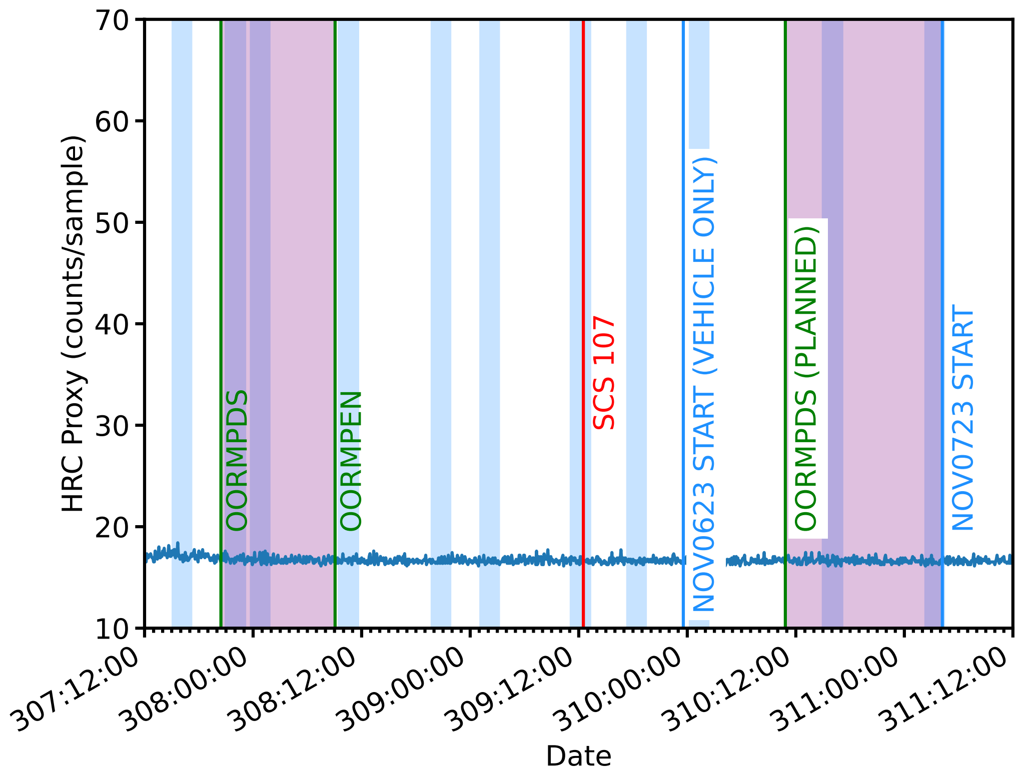

Figure 5: The HRC Shield proxy during the storm. Shaded regions and vertical lines have the same meaning as in Figure 1. Throughout the entire storm, this value was very far away from the trigger value of 245.

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 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.