CHANDRA
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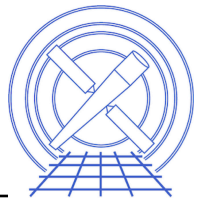

Date: November 12, 2024
From: John ZuHone
To: Chandra Operations Team
Subject: Chandra Radiation Event and Shutdown in October 2024
Cc: MSFC Project Science, CXC Director's Office
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1 Abstract

This memo discusses the thought process that the operations team, especially the ACIS operations team, used during a very high radiation event between October 9-13, 2024. *Chandra* was shut down via an automatic trigger of SCS-107 via the ACIS *txings* algorithm. The key decision points to resume science operations are reviewed, and the details of the storm are presented.

During this storm, the accumulated attenuated ACE P3 fluence was approximately 5.8×10^7. Thanks to the automatic shutdown, ACIS avoided accumulating another $\sim 9.6 \times 10^9$ of P3 fluence. The agreed annual budget for this quantity is 2.0×10^{10}.

2 Introduction

During the days of October 9-13, 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 are near solar maximum.

The ACIS txings rate onboard monitoring software serves 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 substantial 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 October 9-13 2024 Detailed Timeline

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

- 2024:283 **Wednesday October 9, 2024**
- 2024:283:00:00:00 The OCT0724A load is in progress.
- 2024:283:00:25:00 **Comm** begins (60 min).
- 2024:283:01:55:00 Earth-orbiting satellites detect an X1.8-class solar flare. It is Earth-directed and a fast-moving CME is associated with it.
- 2024:283:03:00:00 The GOES proton channels, the HRC Proxy, and the ACE electron channels begin rising sharply, will continue to rise for the next 8-9 hours. The ACE proton channels begin a slower rise.
- 2024:283:03:33:59 SCS-107 runs due to a txings trigger, out of comm.
- 2024:283:09:00:00 ACE P3 reaches a value of ∼3500 and plateaus for the next ∼21 hours.
- 2024:283:13:15:00 **Comm** begins (60 min). The spacecraft comes up with the science loads terminated; ACIS is safe.
- 2024:283:15:47:00 Earth-orbiting satellites detect an X1.4-class solar flare.
- 2024:283:19:20:00 The HRC proxy reaches a maximum value of ∼2100.
- 2024:283:20:30:00 **Comm** begins (60 min).
- 2024:283:22:00:21 Time of RADMON disable from the OCT0724A loads.
- 2024:284 **Thursday October 10, 2024**
- 2024:284:01:15:00 **Comm** begins (60 min).
- 2024:284:05:08:27 Time of perigee.
- 2024:284:06:00:00 ACE P3 begins to slowly increase from a value of ∼4000.
- 2024:284:10:05:00 **Comm** begins (60 min).
- 2024:284:11:03:40 Time of RADMON enable from the OCT0724A loads.
- 2024:284:14:45:00 Space weather alerts go out indicating a CME is approaching Earth. All ACE proton rates increase dramatically. ACE P3 hits a maximum of $\sim 4.7 \times 10^5$. The HRC proxy begins a slow decline that will last for the next ∼9 hours.

- 2024:284:15:15:00 A CME hits Earth's magnetic field, producing a G4-class storm.
- 2024:284:16:30:00 **Comm** begins (60 min).
- 2024:284:22:00:00 ACE proton rates begin to decline dramatically. ACE P3 eventually levels off at a value of ∼2500, and will persist at this level until return to science.
- 2024:284:22:35:00 GOES proton rates begin to decline dramatically.
- 2024:285 **Friday October 11, 2024**
- 2024:285:00:30:00 **Comm** begins (60 min).
- 2024:285:00:20:44 ACIS Ops begins a 24-hour 4-CCD ECS measurement using CAP 1759.
- 2024:285:11:50:00 **Comm** begins (60 min).
- 2024:086 **Saturday October 12, 2024**
- 2024:286:00:20:44 ECS measurement ends.
- 2024:286:01:15:00 **Comm** begins (60 min).
- 2024:286:15:30:00 **Comm** begins (60 min).
- 2024:287 **Sunday October 13, 2024**
- 2024:287:00:15:00 **Comm** begins (60 min).
- 2024:287:01:27:00 First command of the OCT1324B return-to-science loads.

4 Discussion

In the days leading up to October 9th, 2024, number of sunspot regions had been active, activating flares and producing bright aurorae. In the very early hours (2024:283:01:55:00 UTC) of October 9, an X1.8-class solar flare was detected that was earth-directed. Roughly an hour and a half later, GOES proton channels P5 and P7 increased rapidly, followed by a slower decrease in channels P1 and P3 (see Figure 3). The HRC proxy, which is a linear combination of GOES channels, also increased sharply (see Figure 6). The ACE proton rates in all channels also slowly began to rise (see Figures 2 and 1). The ACIS txings rates, also increasing sharply, triggered an autonomous run of SCS-107 at 2024:283:03:33:59, the FI rates having tripped its increasing threshold (see Figures 4 and 5).

The ACIS Ops team and the rest of the Chandra project convened for the daily 9 am ET tagup, and it was decided at this time if txings had not autonomously shut down the

spacecraft at the next comm (which was immediately afterward at 9:15 am ET), that the spacecraft would not be manually shut down. The ACE rates were increasing but not high, and the next HRC observation was not for several days. It was noted that the CME from the X1.8-flare was predicted to arrive by Thursday night local time. The next RADMON disable from the OCT0724A loads was in roughly 9 hours at 2024:283:22:00:21.

At the 9:15 am ET comm, it was discovered that the spacecraft had already been shut down and SCS-107 had been autonomously run by the txings trigger. The science instruments were safe, and the vehicle loads were running. Given that the CME was not expected to arrive until Thursday night, it was decided to wait 24 hours until the next daily tagup to discuss the return to science plan, which would be worked in the meantime. Later in the day, an X1.4-class solar flare was detected. During day 283 and into the early hours of day 284, the ACE P3 rates are roughly constant at a value of ∼2500-3000 (Figure 1). Most of the GOES proton rates and the HRC proxy (Figures 3 and 6) are relatively high and flat during this same period.

The next morning (at roughly 06:00 UTC), the ACE proton rates begin to increase. Roughly 9 hours later, the CME from the original X1.8-class flare hits, and the GOES P1-P5 rates, as well as the ACE rates, begin to increase rapidly. ACE P3 hits a maximum of $\sim 4.7 \times 10^5$. The ACE and GOES rates begin to decline slowly, and then decrease rapidly 7 hours later (at approximately 22:00 UTC). After this, all rates are approximately flat until the return to science.

ACIS Operations ran a 24-hour 4-CCD ECS measurement starting at 2024:285:00:20:44, using CAP 1759. The second step in the long ECS CAP is to check the radiation levels. Since radiation levels were high at the time of CAP review, there was some discussion about under what circumstances the measurement would be allowed to proceed, since txings is running during the measurement and RADMON is enabled, which could cause a trip of SCS-107. This would not be harmful, but undesirable as it would cause unnecessary work. In the end, given that the hard proton rates were declining and near the HRC Proxy trigger level, it was decided to proceed with the measurement.

The storm spanned portions of two science orbits. ACIS was safed for the entire duration of the latter orbit. In the end, the total accumulated fluence for the first orbit was 5.8×10^7. The total ACE P3 fluence that would have been accumulated during these two science orbits had ACIS not been safed is 9.6×10^9. The txings trigger, along with prudent monitoring of space weather and decision-making by the project, prevented the accumulation of this enormous fluence.

5 Data plots for the October 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 October 9-13 storm. Also marked are radiation belt passages, the time of autonomous SCS-107 execution, comm times, and

the start and stop times of a long ECS measurement that was run during the storm (the same times are marked in the rest of the radiation vs. time plots).

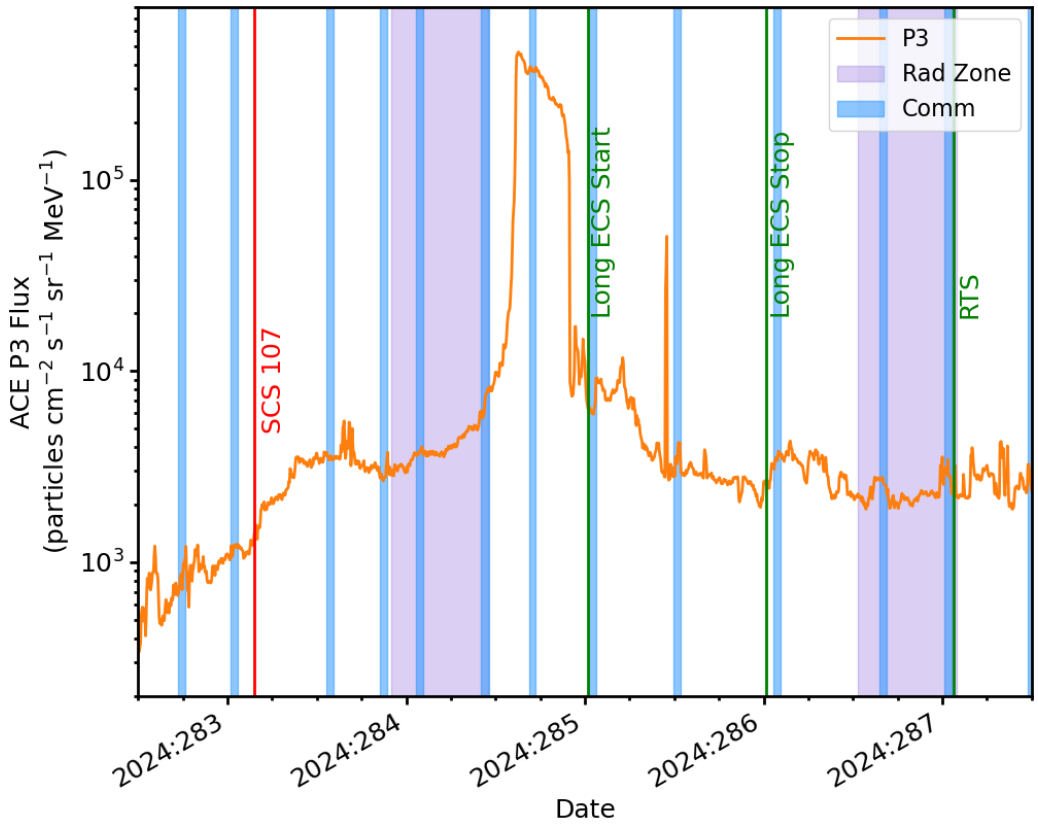

Figure 1: A plot of the ACE P3 flux during the October 2024 storm. Purple shaded regions indicate the radzone passages. Fluence is integrated when ACIS is in focus, and is counted from radzone exit. Blue shaded regions mark scheduled DSN communications.

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 beginning at approximately 2024:284:11:00:00. At this time, the flux in these channels is flatter and harder, which can often point to significant P3 flux occurring downstream.

Figure 3 shows the flux from four GOES proton channels (P1, P3, P5, and P7) during the storm. These higher-energy protons are more representative of the radiation that triggers ACIS txings. These proton channels have a steep increase in flux at the time of the txings trigger, as well as an increase in GOES P1, P3, and P5 at the time of the steep

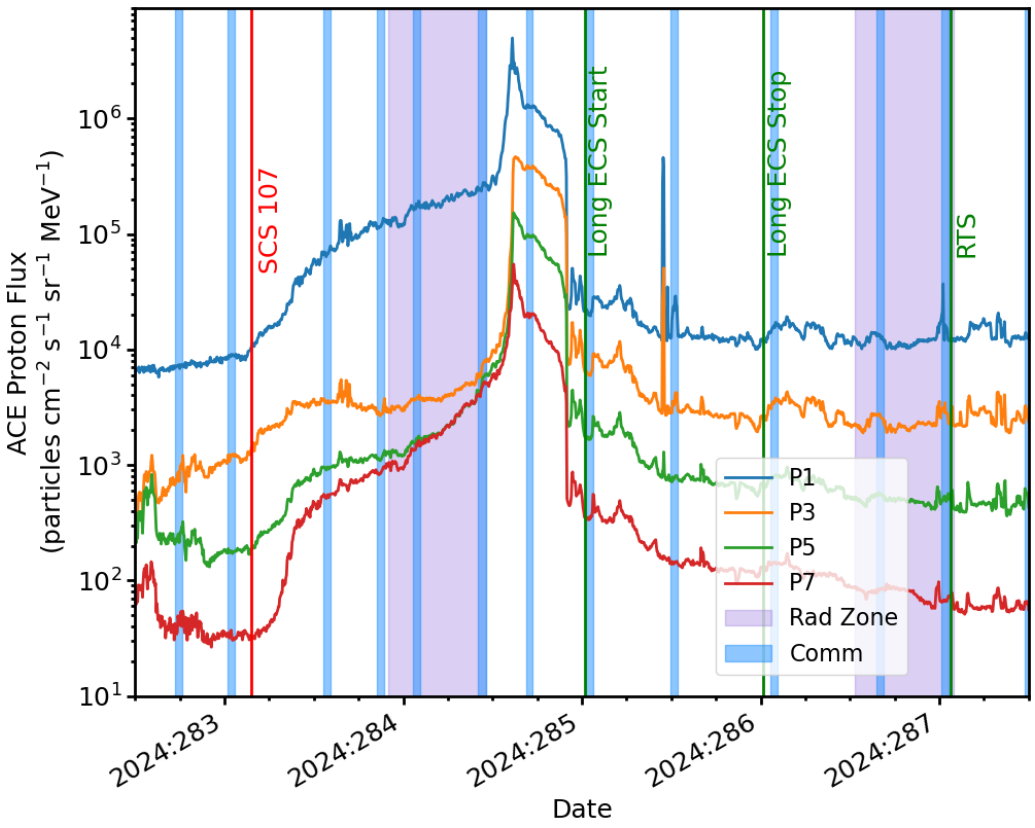

Figure 2: A plot of the flux from four ACE channels P1, P3, P5, and P7 during the October storm. Shaded regions and vertical lines have the same meaning as in Figure 1.

increase in ACE channels.

In Figure 4, we present the ACIS threshold crossings as a function of time for the days of the storm. Both the FI and BI rates passed their trip thresholds at nearly the same time, but the FI rate triggered first. Figure 5 shows a close-up of the txings rates on DOY 282-283.

Finally, Figure 6 shows the HRC Shield Proxy during the storm. 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 science orbit, as it went above its trigger level of 245 at approximately 2024:283:06:30, roughly three hours after the txings trigger.

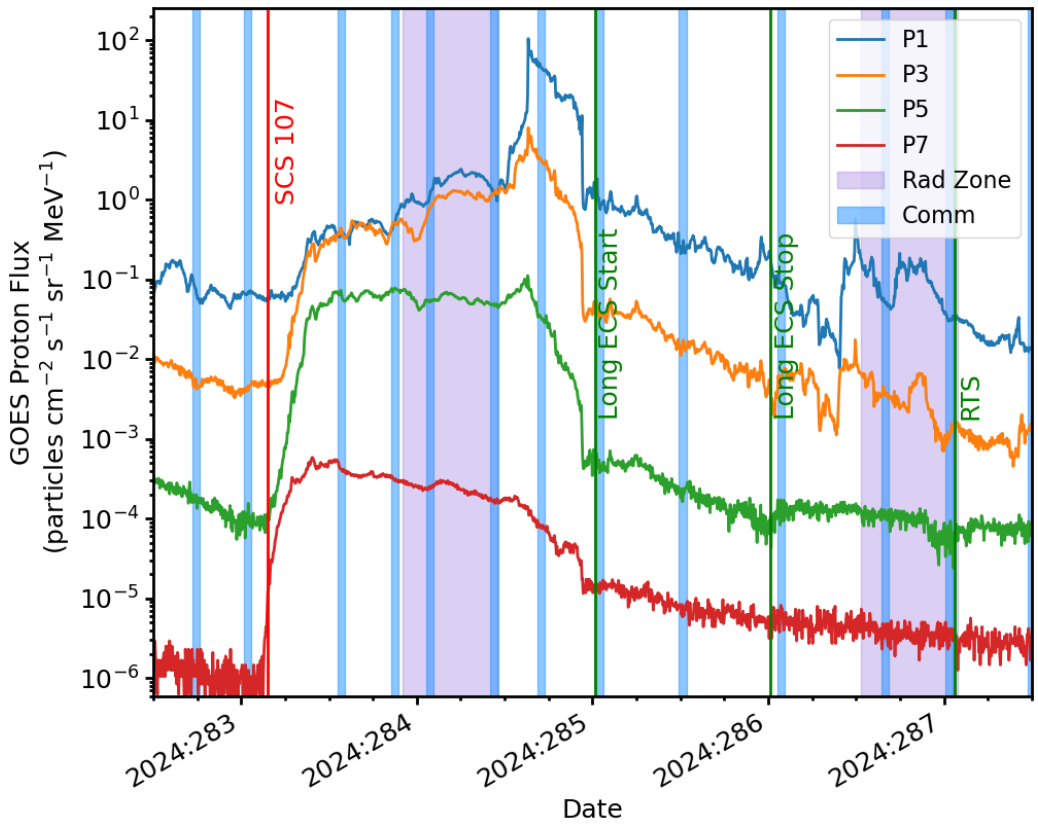

Figure 3: A plot of the flux from four GOES channels P1, P3, P5, and P7 during the October storm. Shaded regions and vertical lines have the same meaning as in Figure 1.

6 Lessons Learned

- The txings trigger shut down the spacecraft early in the storm, but the potentially damaging ACE P3 fluence did not occur until sometime later. Prudent monitoring of space weather and decision-making by the project prevented the accumulation of a large amount of radiation damage to the ACIS CCDs.
- When attempting a long ECS measurement, it is important to discuss and consider the radiation levels at the time of the measurement. In this case, the hard proton rates were declining and near the HRC Proxy trigger level, so it was safe to proceed with the measurement, but in other storms this may not be the case.
- 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.

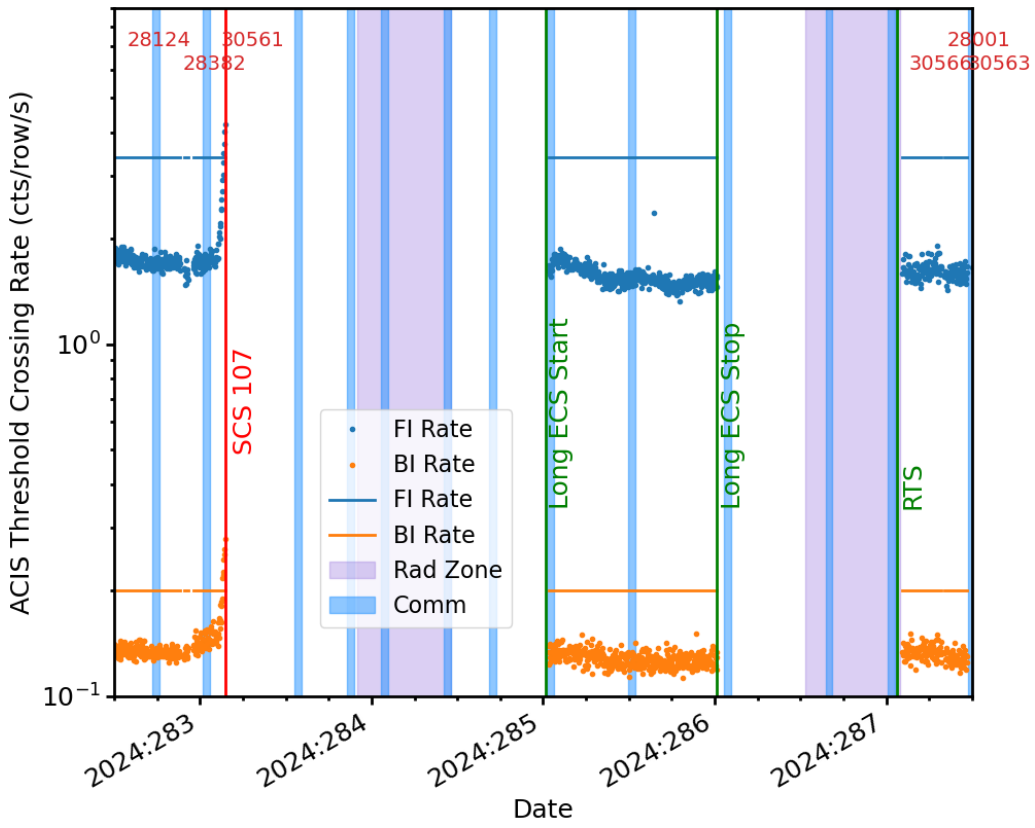

Figure 4: A plot of the txings data during the October 2024 storm. Blue is for FI chips, orange is for BI. The horizontal lines are the increasing values trip thresholds for each type of chip. Shaded regions and vertical lines have the same meaning as in Figure 1.

- The HRC proxy was not above its trigger level before the txings trigger–suggesting that the HRC Anti-Co Shield would not have triggered an autonomous shutdown before txings even if it had been operational. There is currently no similar proxy for the ACIS txings rates which could potentially have predicted the autonomous shutdown. This episode, along with previous ones, motivates the need to produce such a proxy.

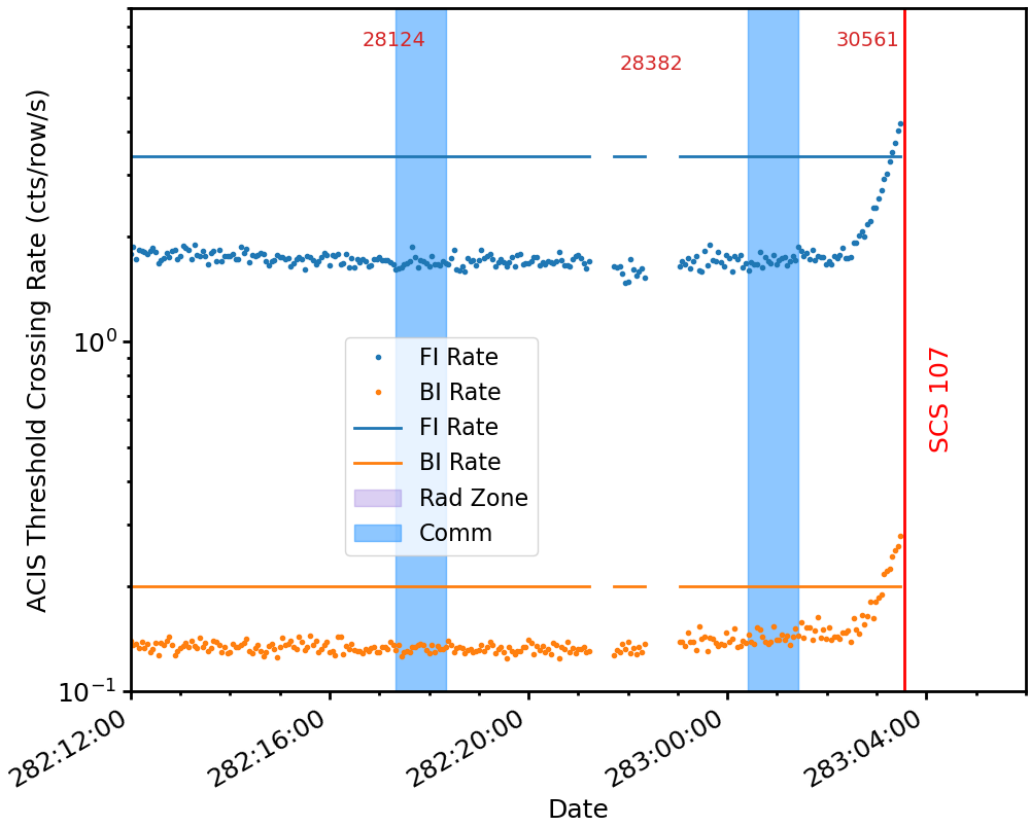

Figure 5: A plot of the txings data during the October 2024 storm, near the time of the txings trigger. All lines, labels, and shaded regions have the same meaning as in Figure 4.

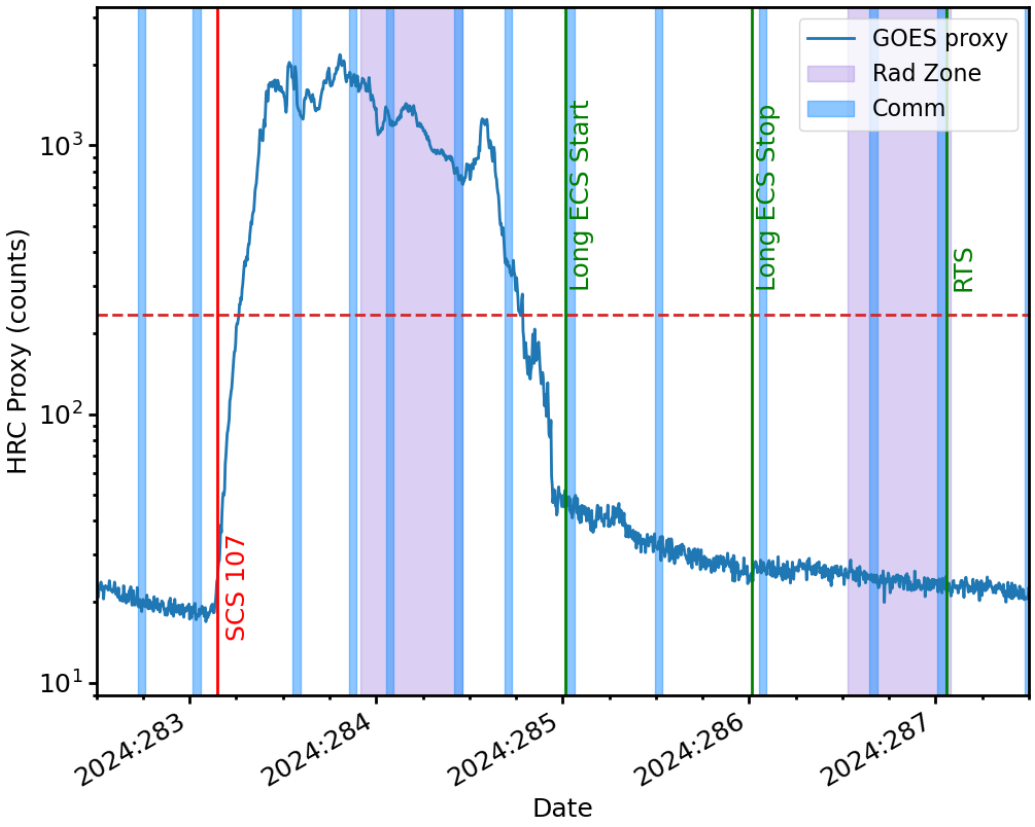

Figure 6: The HRC Shield proxy during the storm. Shaded regions and vertical lines have the same meaning as in Figure 1. The HRC proxy exceeded its trigger value of 245 roughly 3 hours after the txings trigger, and remained at a very high level for the next 36 hours.

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.