# CHANDRA
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**MEMORANDUM**

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| Date: | May 1, 2023 |
| From: | Jack Steiner |
| To: | Chandra Operations Team |
| Subject: | Chandra Radiation Events and Shutdowns in Feb. 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 tumultuous sequence of solar flares from Active Region 3234 including a pair of associated CMEs during the week of February 20, 2023, culminating in a manual SCS-107 the evening of Feb. 26 (early morning Feb. 27 UT).

The key decision points are reviewed. In total, ACIS accumulated an attenuated ACE P3 fluence of $1.7 \times 10^9$. The agreed annual budget for this fluence is $2.0 \times 10^{10}$, with a target ceiling of $< 2.0 \times 10^9$ per orbit. We would have exceeded the orbital threshold if not for the shutdown. The fluence saved by shutting down was $0.9 \times 10^9$.


## 2 Introduction

The solar cycle is ramping up as the Sun exhibits increased levels of activity. This storm was the first to require a commanded radiation shutdown since I joined the ACIS Operations team in 2019, but the second such shutdown took place weeks later in March. Notably, the February shutdown occurred scant days into the return-to-science load (FEB2423A) following the Feb 13th FSS anomaly, which required lengthy and challenging recovery procedures which had been highly taxing on mission planning.

This memo reviews the space-weather activity occurring late in the week of Feb. 20th, explaining the sequence of concerning events, alerts, and the associated timeline for discussion and decision-making. The thought process and arguments which led to shutdown are reviewed, along with the associated impact on the mission.

# 3 Feb. 2023 Detailed Timeline

- Lead-up to FEB2423 RTS Load
  - 2023:044:17:41 **Monday, Feb. 13, 2023** Safemode entered
  - 2023:048:20:16 **Friday, Feb. 17, 2023** X2.2 solar flare
  - 2023:051:10:30 **Monday, Feb. 20, 2023** CME reaches earth
  - 2023:051:14:58 M4.4 solar flare
  - 2023:052:11:11 **Tuesday, Feb. 21, 2023** M1.5 solar flare
  - 2023:052:11:23 M4.7 solar flare
  - 2023:052:20:17 M5.0 solar flare
  - 2023:053:05:12 **Wednesday, Feb. 22, 2023** M1.4 solar flare
  - 2023:053:13:50 M2.6 solar flare
  - 2023:054:06:14 **Thursday, Feb. 23, 2023** M1.5 solar flare
- 2023:055 **Friday, Feb. 24, 2023** FEB2423A RTS load begins execution.
- 2023:055:17:36 A M1.1 flare at 17:15 reported (GOES detection, reported by SpaceWeatherAlerts, hereafter SWA)
- 2023:055:20:50 A M3.7 flare at 20:30pm reported (GOES, via SWA).
- 2023:055:22:35 **Comm** begins (60 min)
- 2023:056:03:30 **Comm** begins (60 min)
- 2023:056:11:15 **Comm** begins (60 min)
- 2023:056:16:00 **Saturday, Feb. 25, 2023** A M1.0 flare at 15:40 reported (GOES, via SWA).
- 2023:056:19:50 **Comm** begins (60 min)
- 2023:056:20:05 A M6.3 flare at 19:44 reported (GOES, via SWA).
- 2023:057 **Sunday, Feb. 26, 2023** Start of orbit, OORMPEN at 04:54:44. ACE P3 rates are modest and variable of order $\sim 10^3$, but higher-energy proton bands are elevated.
- 2023:057:03:30 **Comm** begins (60 min).
- 2023:057:11:55 **Comm** begins (60 min). Elevated ACE P3 rates $> 10^4$ were observed to rise rapidly and then appear to plateau, near $3 \times 10^4$.

- 2023:057:15-18 ACIS Ops discusses radiation environment by email
  - Near start of orbit with very high ACE rates; no grating observations ahead.
  - GOES MeV protons were observed to have peaked earlier and had been declining with lowest channels plateaued.
  - Steady trajectory would give $3{\times}10^9$ dosing, but there was hope of downturn short of another energizing event.
  - Comm opportunities ahead at 17:55 and (evening local, next day UT) 03:30.
  - 2 CMEs expected, but neither had reached Earth. First, from the weaker M3.7 flare, and expected to hit within the next several hours. The second, from the M6.3 flare was expected near belt entry.
  - The first flare was noted to be "possibly a glancing blow" on the CME dashboard, and so was expected to have relatively small impact.
  - Decision made to wait for comm pass to see if *txings* triggered autonomously (it did not).
  - If a critical $5 \times 10^4$ ACE P3 rate had been reached early in comm (it was not, but would have produced $2 \times 10^9$ fluence by the subsequent evening comm), then ACIS Ops would have discussed a possible commanded shutdown.
  - Ultimately, recommendation was to not take any action, but to alert the wider team of the status.
- 2023:057:17:55 **Comm** begins (60 min).
- 2023:057:18:22 **sot_ace_alert** email alert sent noting the current flux and the expectation that $1.0{\times}10^9$ and $2.0{\times}10^9$ fluence levels for the orbit would be exceeded in the hours ahead with no immediate action requested.
- 2023:057:19 DISCOVR shows signs of CME passage; ACE P3 rates spike above 50,000.
- 2023:057:19:18 CME alert received from SWA with expected imminent Earth impact (within one hour), from the M3.7 flare. ACE rates dramatically elevated.
- 2023:057:20 Automated ACE P3 limit alerts received ($1{\times}10^9$ orbital fluence).
- 2023:057:21 ACE P3 rates plateaued to $\sim 2 \times 10^4$.
- 2023:058:01-02 **Monday, Feb. 27, 2023** ACIS Ops discusses whether to call for radiation shutdown
  - Rates still alarmingly elevated and energizing event has occurred.
  - High probability of further flares and new inbound CME expected

  - Steady flux gives expected orbital fluence of $4.4\times10^9$.
  - Benchmark shutdown expected to save $\sim 2.6 \times 10^9$ before factoring in added risk from further flares or CMEs.
  - Group consensus is to advocate for commanded shutdown with an imminent call, prior to the comm ahead.

- 2023:058:02:15 **sot_red_alert** message sent for radiation discussion at 02:45.
- 2023:058:02:45 **Shutdown Discussion**
  - Presented current fluence ($1.7 \times 10^9$) and projected fluence ($4.4 \times 10^9$), high risk of further M or X class flares.
  - Presented windmill animation, the CME scoreboard, and discussed the possibility that the M6.3 flare's CME may impact several hours ahead of belt passage, a substantial exacerbation of the radiation risk.
  - A suggestion was put forward that accumulated radiation shouldn't be considered, only prevented radiation.
  - Shutdown impact on planned/constrained observations in the load ahead was discussed.
  - The conversation rapidly converged on agreement to proceed with the shutdown.
  - Discussion of whether to delay shutdown to end of comm to finish a near-complete science observation was quashed in favor of shutting down while the command link was active.
- 2023:058:03:18:36 **SCS107** recorded by S/C (the CC having come up early).
- 2023:058:03:30 **Comm** (as scheduled) begins (60 min)
- 2023:058:14:40 **Comm** begins (60 min)
- 2023:059:03:00 **Tuesday, Feb. 28, 2023 Comm** begins (60 min)
- 2023:059:07:55 Orbit ends at scheduled time of OORMPDS for belt-entry.
- 2023:059:18:11 A M8.6 flare at 17:50 reported (GOES, via SWA).
- 2023:059:20:03 Time OORMPEN *would have* occurred had the FEB2423A load not been halted.
- 2023:060:01:25 **Wednesday, Mar. 1, 2023** A M1.0 flare at 01:07 reported (GOES, via SWA).
- 2023:060:06:29 OORMPEN at start of the MAR0123A recovery load.

# 4 Feb 2023 Shutdown Overview

The total time which would have been available for science if not for the manual SCS-107 is $\sim$ 141ks (103ks in the orbit which was shut down, and 38ks in the subsequent orbit). The effective (i.e., attenuated) ACE P3 fluence avoided by shutting down was $0.9 \times 10^9$. For comparison, the accumulated attenuated ACE P3 fluence over the orbit prior to shutdown was $1.7 \times 10^9$.

Following the SCS-107, no further flares occurred during the remainder of the orbit, and ACE P3 rates declined significantly by a factor $\sim 5$ after several hours to a flux of several thousand. The second CME did not arrive during the science orbit, which had been a significant point of concern. Instead, it arrived at the safest time for such events, early into belt passage. This CME also produced much weaker impact on the particle rates than we had anticipated (ACE P3 additional fluence associated with its impact was approximately $2 \times 10^8$ over the trend-line).

A sequence of several figures are included which illustrate the behavior and information on the storm at the time of the decision as well as what transpired afterwards. An image of the Sun highlighting the problematic Active Region 3234 distinctly visible is shown in Figure 1. The GOES data during the sequence of events is shown in Figure 2. ACE P3 data during a somewhat broader period of time are shown in Figure 3 in comparison to the sequence timeline. Several ACE proton channels are presented together in Figure 4 to give a sense of the hardness and evolution of the storm. The *txings* rates are presented in Figure 5.

# 5 A Hindsight Perspective

The series of eruptions from Active Region 3234 produced a complex, evolving storm composed of multiple flares and two CMEs, and a broadly elevated risk profile in which further activity was likely. With full knowledge of the storm, in hindsight, a shutdown may not have been necessary. While the fluence saved was appreciable (just shy of 5% of the annual budget), this was several times lower than had been anticipated.

At the time of the shutdown decision, a very steep increase in ACE rates had transpired over a few hours on Feb. 26, a CME had impacted, and the solar-prediction forecast predicted high likelihood of M or X class flares in the day(s) ahead. The rapid and dramatic decline in P3 rates which transpired hours after the first CME impact was not obviously indicated in the data at the time of decision-making and was not anticipated in the discussions.

Had this been expected, it would very likely have impacted the risk evaluation. At the same time, the high stochastic risk of further flares causing further P3 elevation was significant and we may simply have been lucky that the M8.6 flare from Feb. 28 didn't occur 24 hours earlier.

Another favorable surprise was that the second CME was markedly less impactful than had been anticipated (i.e., the CME associated with the M6.3 flare produced an order of magnitude less P3 fluence compared to that from the M3.7 flare which had been expected to produce a "glancing blow"). Perhaps relatedly, the second CME's timing was significantly different than most predictions. Its passage was $\sim$ 12 hours earlier than the average CME scoreboard prediction (on average it was expected to impact shortly after exit from the belts, though the wide-ranging predictions allowed the possibility of an impact during the science orbit in which we shut down).

# 6 Notes

ACE fluxes are given in units of particles $s^{-1}$ $cm^{-2}$ $MeV^{-1}$ $sr^{-1}$, and ACE fluences are in units of particles $cm^{-2}$ $MeV^{-1}$ $sr^{-1}$.

Thanks to Dick Edgar for his thoughtful notes, templates, and rich memos on other radiation storms. Thanks as well to NOAA's SWPC, SWA, ACE, and GOES for their fantastic resources which help us in safely operating ACIS.

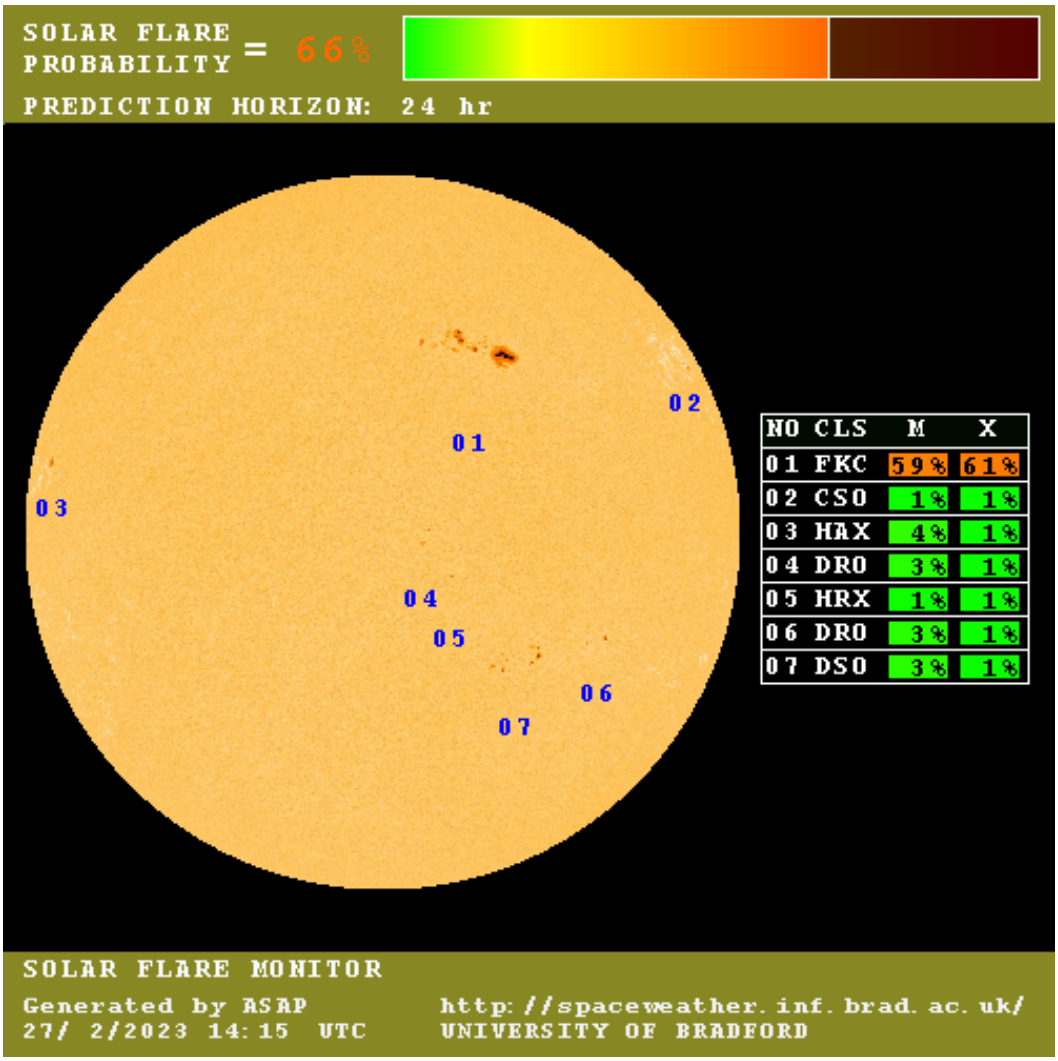


Figure 1: A snapshot of the Bradford Solar Flare Probability taken from Replan Central approximately a half-day after shutdown. "01" on the plot marks Active Region 3234. The flare probability over the remaining 1.2 days in the orbit at the time of the shutdown decision was estimated as $\approx 70\%$, notably with high risk of an X-class flare.

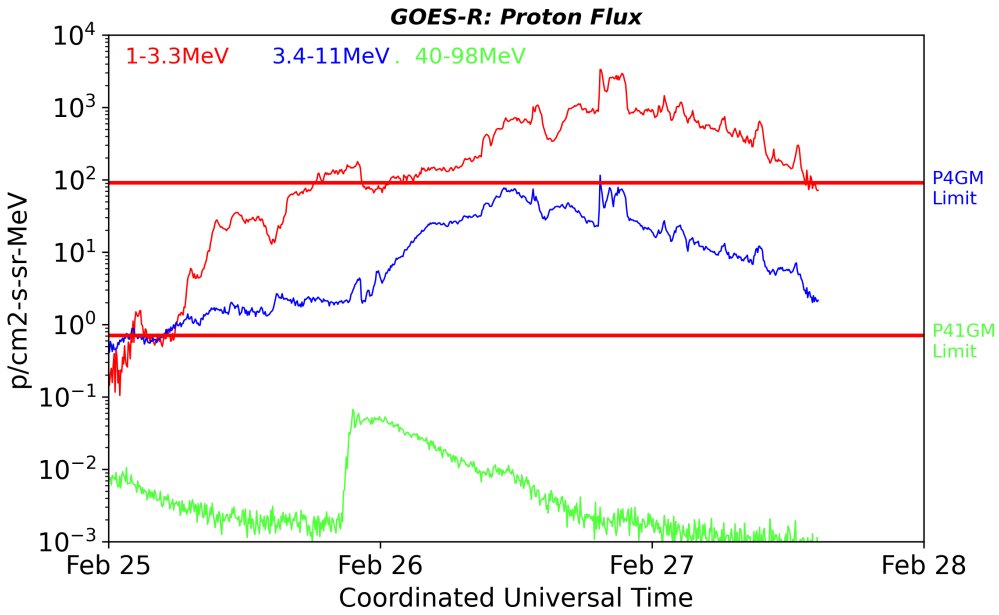


Figure 2: A snapshot of the GOES-R flux taken from Replan Central approximately a half-day after shutdown. The P4GM limit was just crossed several hours prior to the shutdown, corresponding to the impact of the first CME.

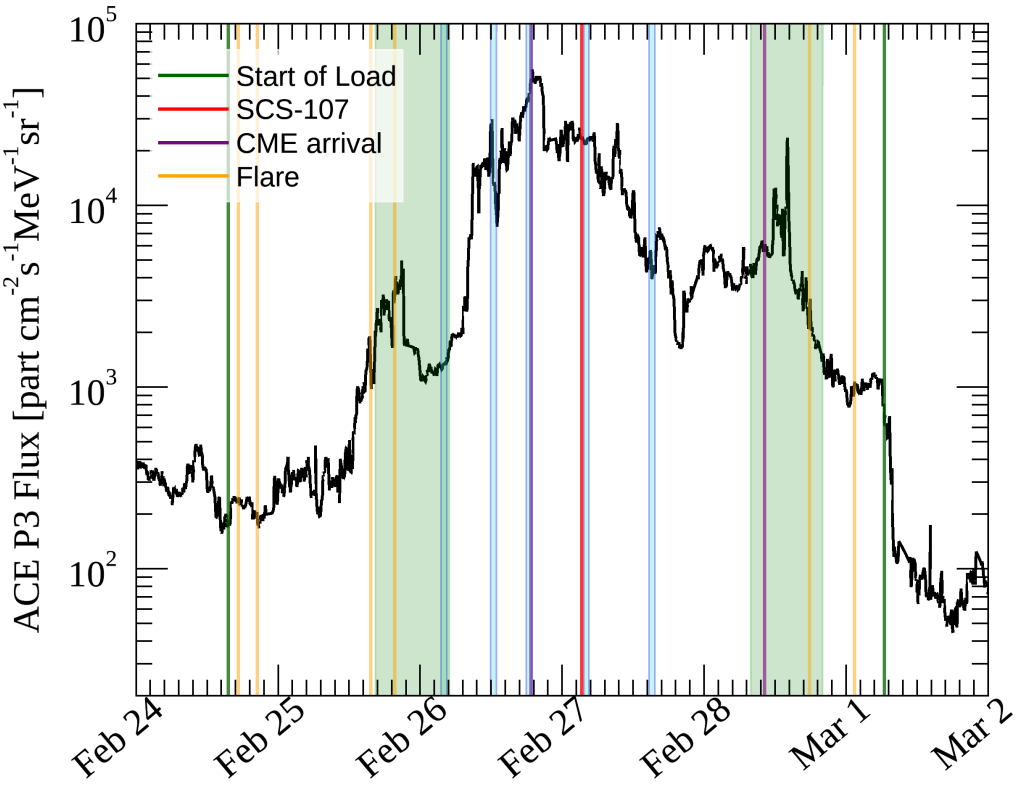


Figure 3: The ACE P3 flux during the storm, with time markers indicating the start of the load (dark green), the commanded SCS-107 (red), and the times of flares (orange) and CMEs (purple). Shaded regions indicate belt passages (green) and several comms of interest (blue).

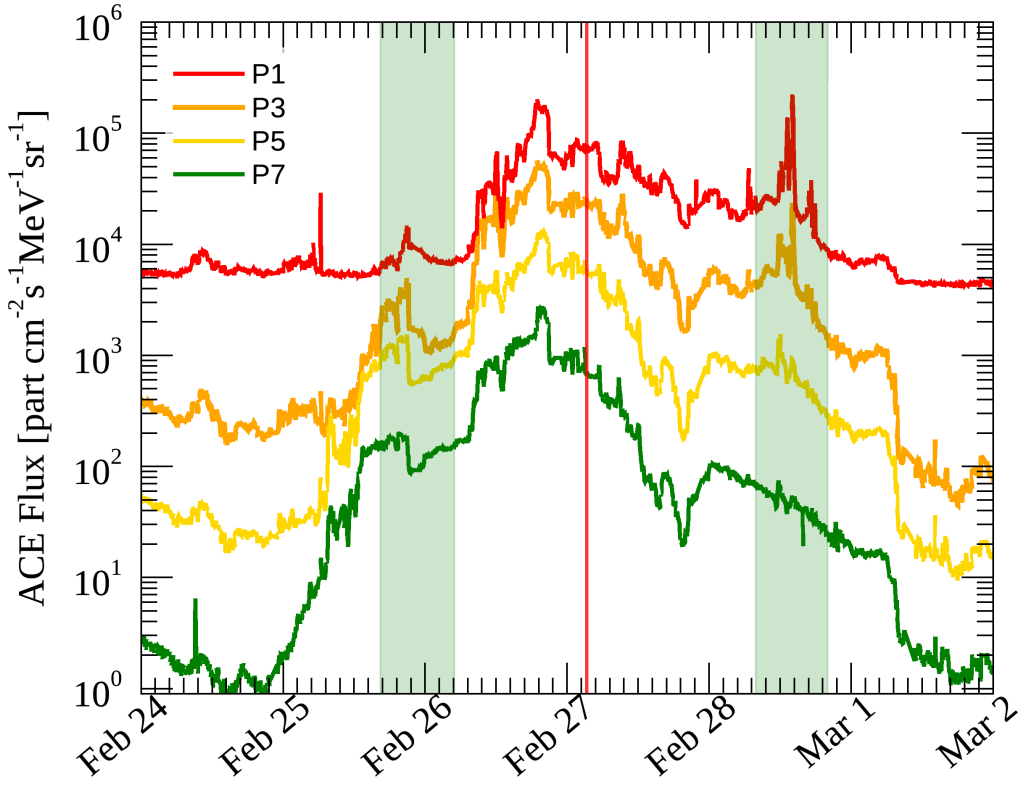


Figure 4: ACE proton bands during the storm event. The red vertical line marks the time of shutdown and green shaded regions mark the belt passages. This storm was relatively soft.

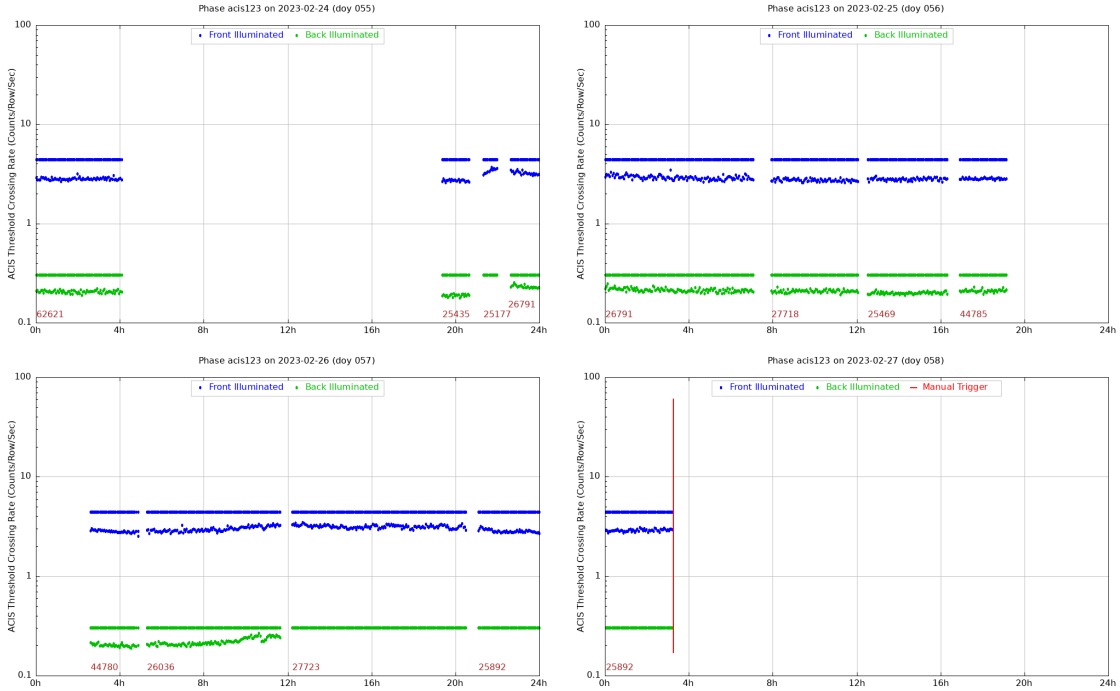


Figure 5: Plots of the *txings* rates and associated limits over the storm's ramp-up, until the manual SCS-107 run. Background levels were noticeably elevated around the time of the M3.7 flare on Feb. 24, and at the time of the very steep rise on Feb. 26, midday. In neither case was trigger particularly close.