A historical fluence analysis of the radiation environment of the Chandra X-ray Observatory and implications for continued radiation monitoring

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ABSTRACT

Now in operation for over 6 years, the Chandra X-ray Observatory (CXO) has sampled a variety of space environments. Its highly elliptical orbit, with a 63.5 hr period, regularly takes the spacecraft through the Earth's radiation belts, the magnetosphere, the magnetosheath and into the solar wind. Additionally, the CXO has weathered several severe solar storms during its time in orbit. Given the vulnerability of Chandra's Charge Coupled Devices (CCDs) to radiation damage from low energy protons, proper radiation management has been a prime concern of the Chandra team. A comprehensive approach utilizing scheduled radiation safing, in addition to both on-board autonomous radiation monitoring and manual intervention, has proved successful at managing further radiation damage. However, the future of autonomous radiation monitoring on-board the CXO faces a new challenge as the multi-layer insulation (MLI) on its radiation monitor, the Electron, Proton, Helium Instrument (EPHIN), continues to degrade, leading to elevated temperatures. Operating at higher temperatures, the data from some EPHIN channels can become noisy and unreliable for radiation monitoring. This paper explores the full implication of the loss of EPHIN to CXO radiation monitoring by evaluating the fluences the CXO experienced during 40 autonomous radiation safing events from 2000 through 2005 in various hypothetical scenarios which include the use of EPHIN in limited to no capacity as a radiation monitor. We also consider the possibility of replacing EPHIN with Chandra's High Resolution Camera (HRC) for radiation monitoring.

Keywords: CCDs, X-ray Astronomy, radiation environment, radiation damage, radiation belts, space missions

1. INTRODUCTION

The Chandra X-Ray Observatory (CXO), launched aboard the Space Shuttle Columbia on July 23rd, 1999, provides the x-ray component of NASA's Great Observatories.[?] The High Resolution Camera (HRC) and the Advanced CCD Imaging Spectrometer (ACIS) are the two main focal plane science instruments on the CXO. The HRC is a micro-channel plate detector, and ACIS is comprised of 8 front-illuminated (FI) and 2 back-illuminated (BI) CCDs.

Early in the mission, it was discovered that the mirrors of the High-Resolution Mirror Assembly (HRMA) on the CXO were far more efficient at scattering low energy protons (0.1-0.5-MeV)[?] toward the focal plane than initially expected, a discovery that manifested itself as a rapid degradation of the charge transfer efficiency (CTE) of the FI CCDs.[?] The soft protons were energetic enough to penetrate the ACIS optical blocking filter (OBF) and the CCD gate structure, and to interact in the depletion region and buried transfer channel of the FI CCDs, creating "charge traps" that remove electrons from charge packets as they are transferred to the frame

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store. The transfer channel of the BI CCDs is protected by 40 μm of Si and showed no increase in charge transfer inefficiency (CTI).[?,?] The bulk of the sustained damage to the FI CCDs occurred while the CXO, with ACIS in the focal plane, traversed Earth's Van Allen radiation belts wherein lie an intense swarm of trapped solar protons.[?] Since this discovery, changes in operating procedure have been implemented to mitigate further damage due to exposure to high radiation.[?]

The Electron, Proton, Helium Instrument (EPHIN) solar energetic particle detector aboard Chandra provides autonomous protection from sudden spikes in radiation levels, and it is this instrument that is the main focus of this paper. Due to degradation of EPHIN's silverized-Teflon multi-layer insulation (MLI),[?] the instrument now experiences much higher operating temperatures than it was originally designed for. This brings into question the sustainability of EPHIN as Chandra's main radiation monitor. In this paper, we provide a summary of the 40 autonomous radiation safing events from 2000 through 2005. Using historical fluence databases from EPHIN, the Advanced Coronal Explorer (ACE) spacecraft, and the Chandra Radiation Model (CRM), we evaluate the accrued fluence in various scenarios that consider the partial or total loss of EPHIN, as well as the use of HRC as a radiation monitor. In Section 2, we provide a brief synopsis of EPHIN and HRC and the use of these instruments as radiation monitors. We describe the databases used in this analysis as well as the methods employed to compute fluences for the various scenarios considered in Section 3. In Section 4, we define each EPHIN scenario and present the fluence results. Lastly, we provide a brief summary of the implications of this study for continued monitoring in Section 5.

2. EPHIN & HRC

EPHIN, a flight spare for the SOlar & Heliospheric Observatory (SOHO), is comprised of 6 silicon detectors (a combination of 3 ion-implanted Si and 3 lithium-drifted Si detectors) with anti-coincidence and a surrounding scintillator read by a photomultiplier tube (PMT). EPHIN collects data in 4 electron channels (0.25-10.4 MeV), 4 proton channels (4.3-53 MeV), 4 helium channels (4.3-53 MeV/nucleon), and an integral channel.[?,?,?,?] The radiation monitor (RADMON) process in Chandra's on-board computer (OBC) continuously evaluates 3 of EPHIN's channels: E1300 (2.6-6.2-MeV electron), P4 (4.3-7.8 MeV proton), and P41 (41-53 MeV proton) for excessive radiation.[?] If any channel exceeds its pre-determined threshold for 10 samples, the OBC initiates the radiation-protection stored command sequence (SCS107).

Operating EPHIN at elevated temperatures leads to the degradation of the lithium-drifted Si detectors through an increase in lithium diffusion.[?] This degradation is evidenced through increased noise in the affected channels that could impact radiation monitoring. As a result of the potential for EPHIN to become unreliable in radiation monitoring, the Chandra team has implemented contingency plans to make use of the HRC's anti-coincidence ("anti-co") shield rates as a radiation monitor.

The HRC consists of 2 microchannel plate (MCP) detectors, HRC-I (a single 10-cm-square MCP), and HRC-S (3 rectangular segments 3-cm x 10-cm each).[?] The HRC anti-co shield, made of plastic scintillator blocks which surround the HRC detector housing, is used to distinguish particles that penetrate the MCP detectors from true X-ray events.[?] As such, it can be used to supplement or replace the EPHIN channel fluxes in radiation monitoring. Unfortunately, the HRC anti-co shield makes for a poor radiation monitor because of its insensitivity to low energy protons; the proton species which cause the most damage in the ACIS CCDs. Comparisons between EPHIN channel fluxes and HRC anti-co shield rates have shown only a rough correlation to the EPHIN P41 channel.[?,?] Given this correlation, we explore the possible use of the HRC anti-coincidence shield as a radiation monitor using the EPHIN P41 channel as a proxy.

3. DATA & METHODOLOGY

All of the results discussed here are derived from historical fluence databases. We begin by assembling a database of EPHIN 5 minute averaged data for the length of Chandra's mission from 1999 to 2005. From this dataset, we compute EPHIN E1300, P4 and P41 fluences as well as normalize all time in this analysis to day of year (DOY) from 1999. We have generated and compiled CRM V2.3 5 minute averaged data, using the observed Kp database, in multiple files spanning from September 1999 through December 2005. Using the archival ACE EPAM level 2 database interface web page,[?] we have gathered ACE EPAM 5 minute averaged data from 1999 to 2005. It is worth noting that due to a disabled P3 channel on ACE, this analysis substitutes the ACE P3' (P3p) channel for P3 from 2003 onward.

To determine exact time frames for each autonomous SCS107 event, we have also constructed multiple databases of Chandra's "orbital events." Included here are the start times of realtime communications (COMs), radiation monitor (RADMON) disable/enable, and a database of autonomous SCS107 events. This information is obtained from the Science Operations Team (SOT) Chandra command load archive.

The analysis looks at each of the 40 SCS107 events from 2000 through 2005 with the objective to calculate the fluence ACIS would have accrued in the 3 EPHIN scenarios discussed in section 4. For each event, the time from that event to the next radmon disable is considered the window for all fluence calculations. In the case where there is no COM between an event and radmon disable, a hypothetical emergency COM is inserted 2 hours after the start of the event. It is assumed that 2 hours would be a reasonable, average response time to aquire an emergency COM. If the emergency COM is later than radmon disable, the COM is then set to the time of radmon disable. The 40 windows are included in Figures 1 through 5 at the end of this paper and show the EPHIN E1300 channel data in black along with CRM V2.3 data in light gray and ACE P3 data in gray. Within each window, one of each of the following may or may not occur and is denoted by a vertical line in the plot: realtime COM (gray), EPHIN P4 channel exceeds radiation safing threshold of 300 (light gray), EPHIN P41 channel exceeds its radiation safing threshold of 8.47 (dark gray). It should be noted that while the units of the EPHIN flux are $counts/sec/cm^2/sr$, the units of the CRM and ACE proton flux are actually $counts/sec/cm^2/sr/MeV$. For presentation purposes, all 3 measurements are plotted along the same y-axis unit of $counts/sec/cm^2/sr$. Fluence calculations are computed by integrating the 5 minute averaged datasets in seconds over the time span of the fluence of interest, ie) an E1300 trip to RADMON disable.

4. ANALYSIS SCENARIOS & RESULTS

4.1. Scenario I: NO EPHIN, NO HRC

In this worst-case scenario, only the scheduled RADMON disables and realtime COMs are relied upon to safe the instruments in an elevated radiation environment; there is no on-board radiation monitor, hence, no autonomous safing. This scenario obviously yields the largest fluences because it allows for the maximum exposure to high radiation. Table 1 below summarizes the fluence calculations and elapsed times for this scenario. In the absolute worst case of relying solely on the scheduled RADMON disable in the weekly load, there would have been an additional 3.4 Ms of exposure to high radiation environments. Such exposure yields an additional CRM fluence of 4.36e10, and ACE P3 fluence of 1.79e11 (comparable to the fluence ACIS has seen outside of the radiation belts for the entire mission!). A slightly less harrowing, and more realistic approach, makes use of scheduled and emergency realtime COMs to safe the instruments. In this case, the 3.4 Ms of exposure is reduced to 246 ks and the fluences are reduced to 7.93e9 (CRM) and 1.12e10 (ACE P3), still a significant exposure considering that the current yearly ACE P3 fluence budget is 2.00e10. The results of this scenario clearly indicate the need for continued on-board autonomous radiation monitoring.

Table 1. NO-EPHIN, NO-HRC Integrated Fluences from Time of SCS107 Event for 40 events (2000-2005). "to next COM (40)" represents the fluence from start of trip to next available COM for all 40 events. "to next RMDS (40)" represents the fluence from start of trip to next RMDS for all 40 events.

description/channel	to next COM (40)	to next RMDS (40)
E1300	1.69e7	4.06e8
P4	1.48e8	2.74e9
P41	2.10e6	5.78e7
CRM v2.3	7.93e9	4.36e10
ACE P3	1.12e10	1.79e11
Total Time (ks)	245.93	3408.96
Avg Time (ks)	6.15	85.22
Max Time (ks)	13.06	175.81
Min Time (ks)	0.07	0.13

4.2. Scenario II: NO EPHIN

This scenario investigates the possibility of using the HRC anti-co shield rates as a radiation monitor; the EPHIN P41 channel is used as a proxy for this measurement. For each SCS107 event, if the EPHIN P41 channel exceeds its radiation safing threshold within the window from the time of SCS107 to the next RADMON disable, the fluence from the E1300/P4 trip to the P41 threshold crossing is calculated. If the P41 channel never exceeds its threshold in that particular event, then the fluence from the time of the trip to the next realtime COM and the next RADMON disable is included. Out of a total of 40 events, there were 17 events in which the P41 channel exceeds its threshold within the window, and 23 in which the P41 channel remains below its threshold. Table 2 below summarizes the fluences and elapsed times for this scenario. An additional ACE P3 fluence of 1.20e9 clearly makes the case that the HRC would make a poor radiation monitor unless steps were taken to increase its sensitivity to high radiation environments, particularly soft proton storms. This fluence is comparable to a single severe solar proton storm. One obvious change would be to lower the threshold required to trip SCS107, as this scenario shows that less than half of the 40 autonomous SCS107 events would have had an EPHIN P41 trip associated with them.

Table 2. NO-EPHIN (HRC as RADMON) Integrated Fluences from Time of SCS107 Event (E1300/P4) for 40 events (2000-2005). "to P41 (17)" represents the fluence from the start of the trip to a P41 threshold crossing for 17 events.

description/channel	to P41 (17)	to next COM (23)	to next RMDS (23)
E1300	3.74e6	1.23e6	4.20e6
P4	4.68e6	9.83e7	4.09e8
P41	1.67e5	4.15e4	2.16e5
CRM v2.3	6.97e8	4.78e9	1.16e10
ACE P3	1.20e9	6.10e9	6.01e10
Total Time (ks)	92.28	129.62	1349.07
Avg Time (ks)	7.10	5.64	58.66
Max Time (ks)	72.22	13.06	173.78
Min Time (ks)	0.06	0.07	0.13

4.3. Scenario III: NO EPHIN E1300

The final scenario considered is the loss of the EPHIN E1300 channel for radiation monitoring. For each event, we determine if the EPHIN E1300 channel tripped the radiation monitor. If this is the case, we calculate the fluence from that trip to an EPHIN P4 and/or P41 threshold crossing, or trip, if one or both exist. If there are no P4 or P41 threshold crossings in that event following the E1300 trip, we calculate the fluence to the next realtime COM and the next RADMON disable. Out of the 40 SCS107 events, there are 16 triggered by the EPHIN E1300 channel. In 10 out of those 16 cases, the EPHIN P4 channel would have exceeded its threshold after the E1300 trip. In 11 out of those 16 cases, the EPHIN P41 channel would have exceeded its threshold after the E1300 trip. Because of overlap in the P4 and P41 trips, we also consider the fluence to either a P4 or P41, which ever occurs first; there are 13 such cases. In only 3 out of the 16 cases, neither the EPHIN P4 or P41 channels would have exceeded their radiation safing thresholds. It is for these 3 cases that fluences to the next realtime COM and the next RADMON disable are calculated. Table 3 below summarizes these findings. In the absence of the EPHIN E1300 channel, there would have been an additional 89 ks exposure to high radiation if the P4 channel had tripped the radiation monitor, and 93 ks if the P41 channel had tripped. Relying on the P4 channel, an additional CRM fluence of 2.21e8 and ACE P3 fluence of 3.40e9 would have accrued. The additional fluences from an E1300 trip to a possible P41 trip would have been 6.97e8 (CRM) and 1.22e9 (ACE P3). Relying on which ever channel exceeds its threshold first between P4 and P41, there is an additional exposure of 170 ks, with a CRM fluence of 5.48e7 and ACE P3 fluence of 3.98e9. These fluences are all comparable to approximately 2 severe solar proton storms. Based on this scenario, it appears that on-board radiation monitoring could continue without the EPHIN E1300 channel with a moderate increase in exposure to high radiation.

5. CONCLUSIONS

The results of a study on the effects of the loss of Chandra's radiation monitor, EPHIN, were presented. Specifically, three scenarios were considered: 1) the complete loss of any on-board radiation monitor (no EPHIN, no

Table 3. NO-EPHIN E1300 Integrated Fluences from time of E1300 SCS107 trip for 16 events (2000-2005)

descrip/chan	to P4 (10)	to P41 (11)	to P4 or P41 (13)	to next COM (3)	to next RMDS (3)
E1300	5.51e6	4.23e6	8.97e6	6.10e4	8.54e4
P4	1.01e7	4.43e6	1.41e7	3.14e5	4.22e5
P41	1.31e6	1.60e5	1.40e6	6.74e2	7.04e2
CRM v2.3	2.21e8	6.97e8	9.18e8	5.48e7	3.85e8
ACE P3	3.40e9	1.22e9	3.98e9	3.59e6	6.49e6
Tot Time (ks)	88.95	93.40	169.76	10.83	79.64
Avg Time (ks)	8.89	8.49	13.06	3.61	26.55
Max Time (ks)	24.67	72.22	72.22	7.48	73.08
Min Time (ks)	0.07	0.06	0.06	0.13	3.21

HRC), 2) the use of HRC as a radiation monitor (using the EPHIN P41 channel as a proxy for the HRC anti-co shield rates), and 3) the loss of the EPHIN E1300 channel in radiation monitoring. For each scenario, the additional exposure to high radiation was presented in terms of elapsed time and fluences. Based on this analysis, it is clear that the loss of all on-board radiation monitoring would have yielded unacceptable fluences on the order of the mission fluence to date. The use of HRC as a radiation monitor would have mitigated the additional exposure to high radiation to some degree, but some steps would need to be taken to increase the sensitivity to elevated radiation. Lastly, this analysis shows that relying solely on the EPHIN P4 and P41 channels for radiation monitoring in the absence of the E1300 channel would have exposed the spacecraft to moderately large doses of additional fluence on the order of 2 severe solar proton storms and, in 3 out of 16 E1300 trips, would not have safed the instruments at all. For reference, the yearly ACE P3 fluence budget is 2e10, while the single worst orbital fluence experienced was 4e10. Table 4 summarizes the individual results for each of the 40 trips, and Table 5 shows the ACE P3 orbital and summed fluences for a 1 month period in 2003 during a particularly severe solar proton storm and more recent data from January of 2006 during a relatively quiet period.

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Table 4. Summary table for all 40 autonomous SCS107 events

#	TP4(ks)	TP41(ks)	TCOM(ks)	TRMDS(ks)	P3fluP4	P3fluP41	P3fluCom	P3fluRMDS
1	0.20	....	5.84	133.30	....	....	1.805E+09	9.987E+09
2	0.20	....	25.13	171.74	....	....	9.724E+08	7.161E+09
3	0.79	1.70	2.62	116.37	2.649E+06	1.929E+07	4.405E+07	1.008E+10
4	0.07	1.70	8.93	174.56	....	1.929E+07	1.209E+09	9.512E+09
5	5.11	1.44	16.60	144.25	2.719E+08	6.674E+07	1.239E+09	1.461E+10
6	0.06	....	29.26	46.18	....	....	7.853E+08	9.330E+08
7	0.07	1.44	16.27	170.49	....	6.674E+07	3.406E+08	4.469E+09
8	....	5.97	7.15	135.40	....	4.047E+08	4.808E+08	1.212E+10
9	19.15	4.46	17.06	147.67	8.192E+08	1.741E+08	7.191E+08	2.690E+10
10	0.07	4.46	9.84	168.99	....	1.741E+08	4.986E+08	3.772E+09
11	10.70	1.51	3.08	19.15	4.836E+08	5.894E+07	1.260E+08	8.845E+08
12	12.40	2.56	21.84	34.84	1.745E+09	3.169E+08	2.924E+09	4.572E+09
13	12.20	0.26	10.16	136.05	1.591E+08	....	1.340E+08	9.580E+08
14	14.76	0.07	20.21	171.75	1.109E+09	....	1.495E+09	1.242E+10
15	0.07	....	6.11	133.44	....	....	1.272E+09	1.502E+10
16	0.06	....	5.24	173.78	....	....	1.189E+08	1.339E+10
17	....	1.70	31.68	126.54	....	9.499E+06	3.432E+08	3.509E+09
18	0.06	....	7.15	8.66	....	....	4.941E+08	6.200E+08
19	0.07	....	0.13	0.13	....	....	....	....
20	0.07	....	7.15	8.01	....	....	8.836E+04	9.938E+04
21	0.53	....	0.07	17.38	7.233E+05	....	....	7.068E+06
22	0.06	....	9.05	14.63	....	....	7.899E+06	1.250E+07
23	0.07	....	10.76	13.12	....	....	3.074E+05	3.603E+05
24	8.59	....	4.06	89.28	2.333E+07	....	1.151E+07	1.088E+08
25	5.57	0.06	26.83	175.81	1.580E+07	....	3.041E+08	8.897E+09
26	1.90	0.07	25.58	165.18	4.311E+06	....	5.749E+07	5.517E+09
27	0.07	....	7.94	98.46	....	....	1.396E+06	8.710E+07
28	0.20	....	1.31	1.31	....	....	1.061E+05	1.061E+05
29	0.20	....	3.21	3.21	....	....	3.492E+06	3.492E+06
30	0.06	....	20.66	167.48	....	....	2.614E+09	3.813E+09
31	0.07	....	4.01	4.01	....	....	1.354E+07	1.354E+07
32	0.07	....	0.13	3.35	....	....	....	1.207E+06
33	0.13	....	3.34	51.04	....	....	5.398E+08	4.963E+09
34	0.06	0.26	10.10	78.65	....	....	4.315E+07	6.008E+08
35	0.06	0.26	1.18	10.69	....	....	4.315E+07	1.770E+08
36	0.06	....	2.62	2.62	....	....	1.422E+05	1.422E+05
37	0.07	....	13.06	104.76	....	....	1.241E+07	3.882E+09
38	0.07	....	7.48	73.08	....	....	1.021E+05	1.788E+06
39	....	72.22	6.16	83.51	....	1.4751E+08	4.656E+06	1.859E+08
40	24.67	.....	9.51	30.11	3.5215E+07	....	1.397E+07	4.177E+07

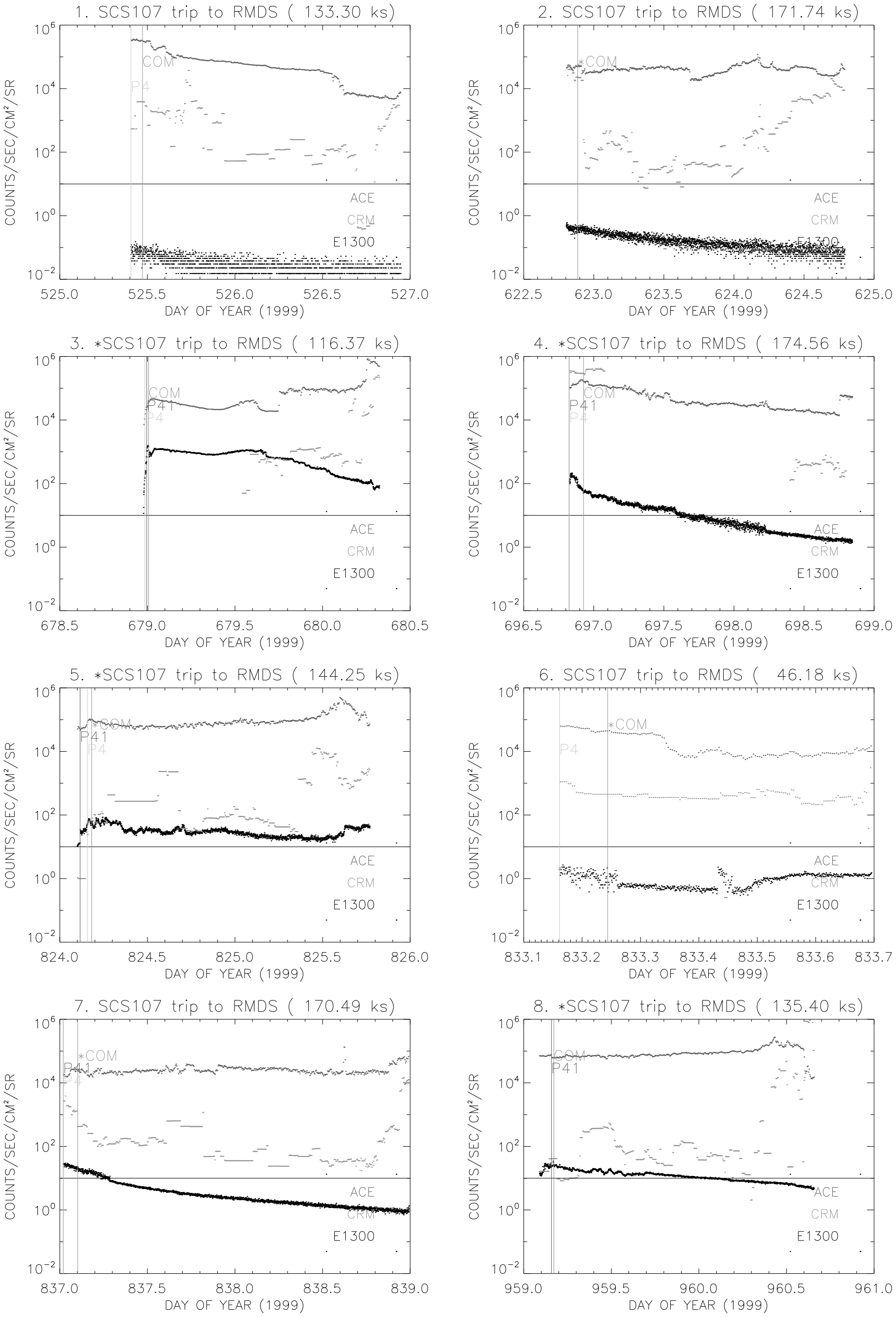
NOTE: "TP4" is the time from an SCS107 event to a P4 trip ("..." indicates no trip and/or no fluence calculation). "P3fluP4" is the ACE P3 fluence integrated over the corresponding channel's time (in this case, P4) from the SCS107 event.

Table 5. Archival ACE P3 Fluence for Oct-Nov 2003 & Jan 2006

YEAR	MO	DAY	HHMN	DOY	SECS	Orbital	Summed
2003	10	28	614	301	17040	2.576e+08	1.177e+11
2003	10	30	2144	303	17040	3.507e+08	1.181e+11
2003	11	2	1309	306	17040	4.076e+10	1.588e+11
2003	11	5	439	309	17040	2.686e+09	1.615e+11
2003	11	7	2004	311	17040	0.000e+00	1.615e+11
2003	11	10	1134	314	17040	4.069e+08	1.619e+11
2003	11	13	304	317	17040	7.793e+07	1.620e+11
2003	11	15	1834	319	17040	1.514e+08	1.622e+11
2003	11	18	959	322	17040	1.485e+08	1.623e+11
2003	11	21	124	325	17040	1.278e+08	1.624e+11
2003	11	23	1654	327	17040	5.567e+08	1.630e+11
2003	11	26	819	330	17040	1.393e+09	1.644e+11
2003	11	28	2349	332	17040	1.733e+08	1.646e+11
2006	1	1	413	1	15180	1.070e+06	2.452e+11
2006	1	3	1938	3	70681	7.585e+06	2.452e+11
2006	1	6	1103	6	39780	1.243e+06	2.452e+11
2006	1	9	238	9	9481	5.562e+05	2.452e+11
2006	1	11	1803	11	64981	2.326e+06	2.452e+11
2006	1	14	933	14	34380	2.419e+06	2.452e+11
2006	1	17	58	17	3481	4.820e+06	2.452e+11
2006	1	19	1628	19	59280	2.416e+06	2.452e+11
2006	1	22	753	22	28380	1.717e+06	2.452e+11
2006	1	24	2318	24	83881	1.039e+07	2.452e+11
2006	1	27	1448	27	53281	3.388e+06	2.452e+11
2006	1	30	613	30	22381	3.981e+06	2.453e+11

NOTE: ACE P3 orbital and summed fluences for a 1 month period in 2003 during one of the worst solar proton storms experienced in the mission. The orbital fluence on 11/2/03 was 2 times the yearly budget (2e10)! The second half of this table shows the ACE P3 orbital and summed fluences for the month of January 2006. The total ACE P3 mission fluence to date is 2.45e11.

APPENDIX A. FIGURES



1. SCS107 trip to RMDS (133.30 ks)

2. SCS107 trip to RMDS (171.74 ks)

3. *SCS107 trip to RMDS (116.37 ks)

4. *SCS107 trip to RMDS (174.56 ks)

5. *SCS107 trip to RMDS (144.25 ks)

6. SCS107 trip to RMDS (46.18 ks)

7. SCS107 trip to RMDS (170.49 ks)

8. *SCS107 trip to RMDS (135.40 ks)

Figure 1. EPHIN E1300 (black data points), CRM V2.3 mean proton flux data (light gray data points), and ACE P3 (gray data points) as a function of time for an SCS107 event. Black horizontal lines correspond to the E1300 SCS 107 limit. Gray vertical lines represent the time of the next COM (note: a '*' preceding COM indicates that the COM was artificially inserted for fluence estimates), while light gray represents the P4 SCS107 threshold trip (300), and dark gray represents the P41 SCS107 threshold trip (8.47). A '*' preceding SCS107 in the title of the plot indicates that the trip was caused by the EPHIN E1300 channel. The duration of this event from the time of the SCS107 trip to the next RADMON disable is listed in the title of each plot.

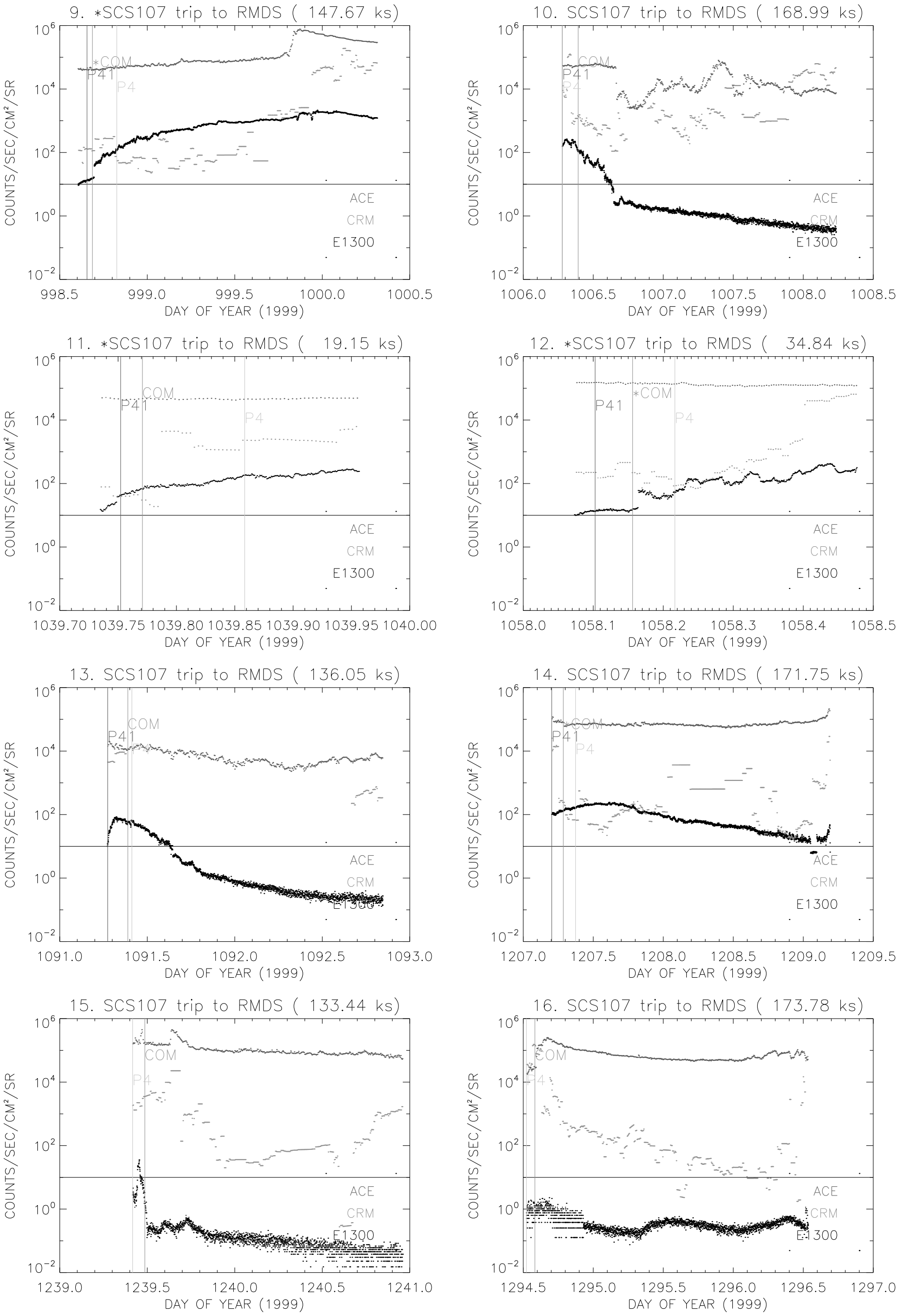


Figure 2. EPHIN E1300 (black data points), CRM V2.3 mean proton flux data (light gray data points), and ACE P3 (gray data points) as a function of time for an SCS107 event. Black horizontal lines correspond to the E1300 SCS 107 limit. Gray vertical lines represent the time of the next COM (note: a '*' preceding COM indicates that the COM was artificially inserted for fluence estimates), while light gray represents the P4 SCS107 threshold trip (300), and dark gray represents the P41 SCS107 threshold trip (8.47). A '*' preceding SCS107 in the title of the plot indicates that the trip was caused by the EPHIN E1300 channel. The duration of this event from the time of the SCS107 trip to the next RADMON disable is listed in the title of each plot.

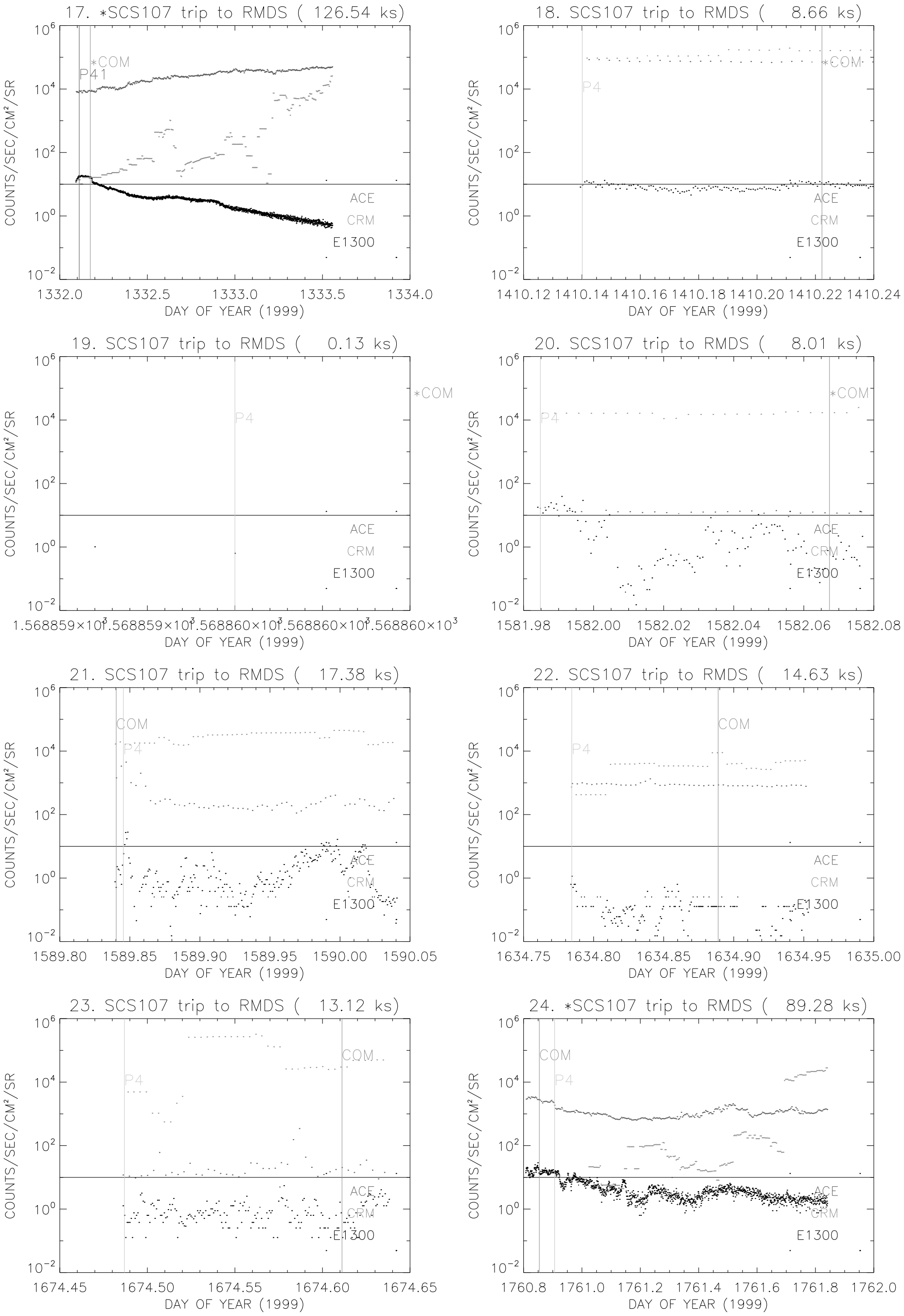


Figure 3. EPHIN E1300 (black data points), CRM V2.3 mean proton flux data (light gray data points), and ACE P3 (gray data points) as a function of time for an SCS107 event. Black horizontal lines correspond to the E1300 SCS 107 limit. Gray vertical lines represent the time of the next COM (note: a '*' preceding COM indicates that the COM was artificially inserted for fluence estimates), while light gray represents the P4 SCS107 threshold trip (300), and dark gray represents the P41 SCS107 threshold trip (8.47). A '*' preceding SCS107 in the title of the plot indicates that the trip was caused by the EPHIN E1300 channel. The duration of this event from the time of the SCS107 trip to the next RADMON disable is listed in the title of each plot.

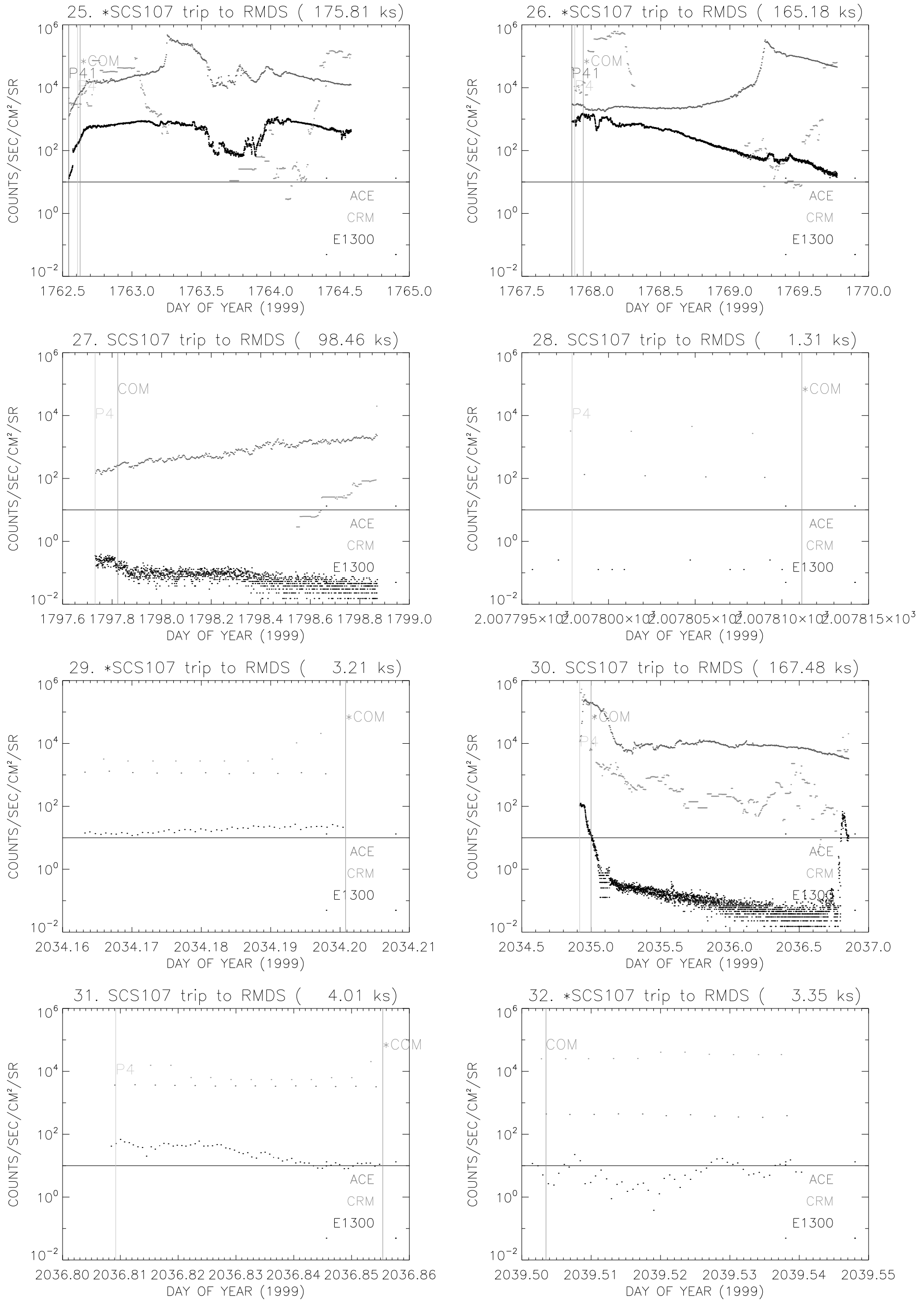


Figure 4. EPHIN E1300 (black data points), CRM V2.3 mean proton flux data (light gray data points), and ACE P3 (gray data points) as a function of time for an SCS107 event. Black horizontal lines correspond to the E1300 SCS 107 limit. Gray vertical lines represent the time of the next COM (note: a '*' preceding COM indicates that the COM was artificially inserted for fluence estimates), while light gray represents the P4 SCS107 threshold trip (300), and dark gray represents the P41 SCS107 threshold trip (8.47). A '*' preceding SCS107 in the title of the plot indicates that the trip was caused by the EPHIN E1300 channel. The duration of this event from the time of the SCS107 trip to the next RADMON disable is listed in the title of each plot.

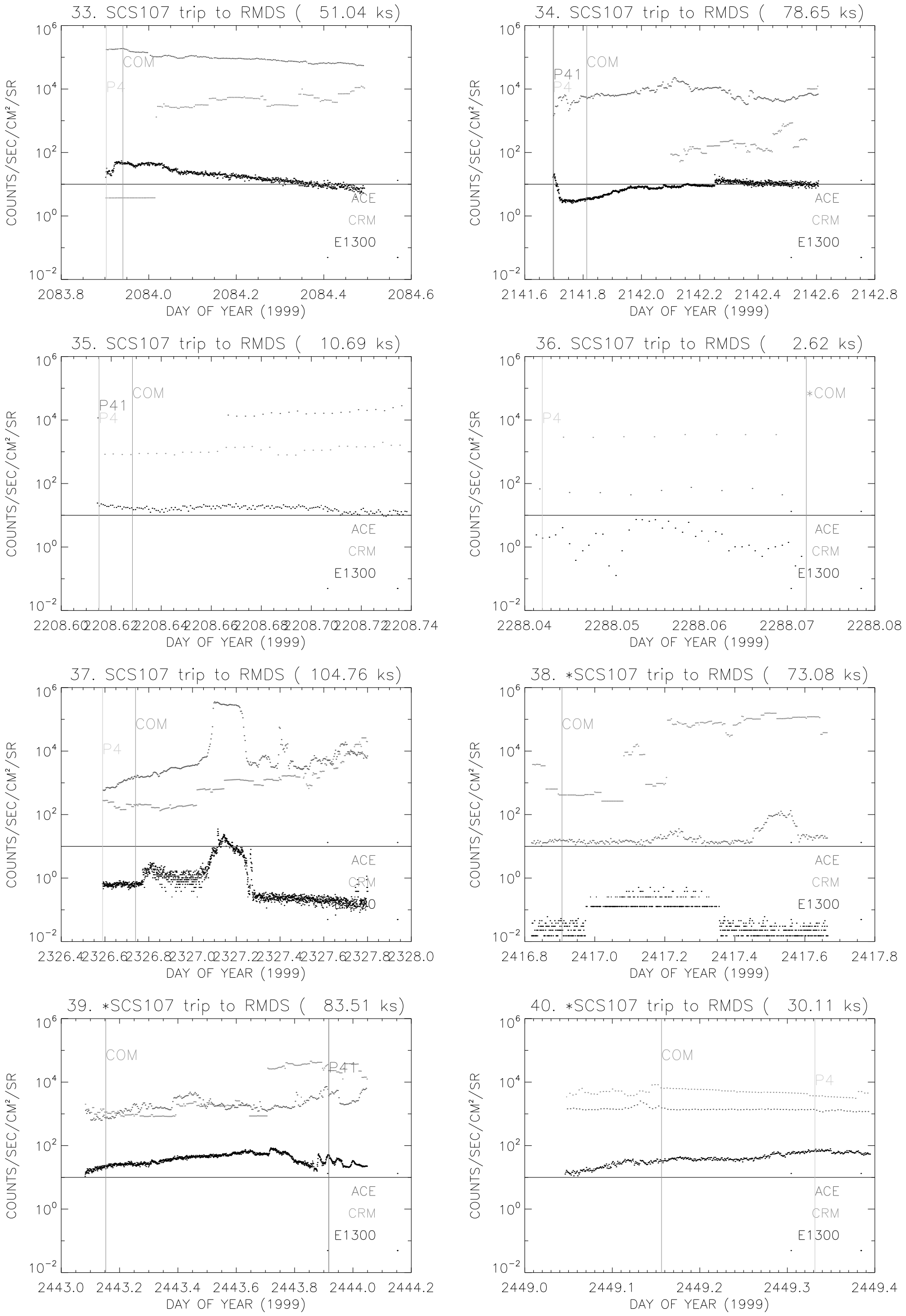


Figure 5. EPHIN E1300 (black data points), CRM V2.3 mean proton flux data (light gray data points), and ACE P3 (gray data points) as a function of time for an SCS107 event. Black horizontal lines correspond to the E1300 SCS 107 limit. Gray vertical lines represent the time of the next COM (note: a '*' preceding COM indicates that the COM was artificially inserted for fluence estimates), while light gray represents the P4 SCS107 threshold trip (300), and dark gray represents the P41 SCS107 threshold trip (8.47). A '*' preceding SCS107 in the title of the plot indicates that the trip was caused by the EPHIN E1300 channel. The duration of this event from the time of the SCS107 trip to the next RADMON disable is listed in the title of each plot.