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The Periods of Enhanced Background Experienced by the ACIS Instrument on the Chandra X-ray Observatory

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Abstract.

We have analyzed data acquired during the Orbital Activation and Checkout (OAC) and Guest Observer (GO) phases of the Chandra X-ray Observatory (CXO) mission in order to characterize the background of the *Advanced CCD Imaging Spectrometer* (ACIS) instrument produced by energetic particles. This paper will focus exclusively on the periods with enhanced background. The ACIS instrument contains 8 Front-Illuminated (FI) CCDs and 2 Back-Illuminated (BI) CCDs. The FI and BI CCDs exhibit dramatically different responses to enhancements in the particle flux. The FI CCDs show relatively little increase in the overall count rate, typical increases are $1 - 5$ cts s^{-1} above the quiescent level; the BI CCDs can show large excursions to as high as 100 cts s^{-1} above the quiescent level. The durations of these intervals of enhanced background are also highly variable ranging from 500 s to 10^4 s. These periods of enhanced background are sometimes but not always associated with increased particle flux when Chandra is near the radiation belts.

The spatial distribution of these enhanced background events is inconsistent with the vignetting pattern of the telescope. The spectral distribution is a continuum across the entire bandpass from 0.3 to 10.0 keV. The two BI CCDs on Chandra respond similarly to these enhanced background rates. The traditional techniques of distinguishing background events from x-ray events are ineffective in excluding these background events.

1. INTRODUCTION

The Chandra X-ray Observatory (CXO) is the third of NASA's great observatories in space. CXO was launched just past midnight on July 23, 1999 aboard the space shuttle *Columbia* on the STS-93 mission. CXO was placed into a higher orbit by an Inertial Upper Stage (IUS) booster and then used its own propulsion system to achieve a final orbit with a perigee 10,000 km, an apogee of 140,000 km, an inclination of 28.5° and a period of ~ 64 hr.

The CXO carries two focal plane science instruments: the *Advanced CCD Imaging Spectrometer* (ACIS) and the *High Resolution Camera* (HRC). The Observatory also possesses two objective transmission gratings: a *Low Energy Transmission Grating* (LETG) that is to be primarily used with the HRC, and the *High Energy Transmission Grating* (HETG) that is to be primarily used with

the ACIS. In addition to these instruments, Chandra also carries a radiation monitor – the *Electron, Proton, Helium Instrument* (EPHIN) particle detector. This paper will discuss data from the ACIS and EPHIN instruments.

ACIS was developed by a team from the Massachusetts Institute of Technology (Bautz et al. 1998) and the Pennsylvania State University (Garmire et al. 1992) and is the primary scientific instrument aboard CXO, currently conducting $\sim 75\%$ of the observations. It contains two arrays of CCDs, one optimized for imaging and the other for spectroscopy as the readout detector for the HETG. The ACIS imaging array contains 4 Front-Illuminated (FI) CCDs configured in a 2×2 array and the spectroscopy array contains 2 Back-Illuminated (BI) CCDs and 4 FI CCDs configured in a 1×6 array.

EPHIN was developed by the University of Kiel (Muller-Mellin et al. 1995 and Sierks 1997) and serves as the radiation monitor for CXO. EPHIN is nearly identical to the instrument flown on the Solar and Heliospheric Observatory (SOHO). EPHIN provides count rates for electrons in 4 bandpasses spanning the energy range from 250 keV to 10 MeV and for protons and He isotopes in 4 bandpasses spanning the range 4 MeV/n to 53 MeV/n. In this paper, we will utilize the lowest energy electron channel, called E150, which is sensitive to electrons with energies between 250 and 700 keV.

2. Correlation of ACIS Enhanced Background Periods with EPHIN Count Rates

2.1. ACIS Observations and Configurations

Essentially as soon as the outer cover of the CXO satellite was opened and celestial observations were begun, it was noticed that the background rate observed by ACIS was highly variable. It was natural to explore the possibility that these periods of enhanced background in ACIS were correlated with increases in the EPHIN count rates. We have examined numerous datasets searching for such a correlation. We have selected a few examples for this paper which represent some of the most extreme cases of enhanced background in order to optimize our search for a correlation. We presented a preliminary analysis in our SPIE 2000 paper (Plucinsky & Virani 2000) and extend that analysis in this paper. Table 1 lists the observation ID numbers, start and stop times, event rejection criteria, and the focal plane temperature.

It is important to note that the ACIS instrument performs event selection and screening on-board and the parameters used in this selection and screening varied over the course of these observations. Most importantly, ACIS can reject events on board based on their morphology (each event is assigned a code to describe how the charge splits in a 3×3 pixel event island) and their total amplitude. The on-board rejection criteria were changed between OBSIDs 1266 and 303. The early observations rejected ASCA g7 events and used no event amplitude cutoff; the latter observations rejected flight grades b24,66,107,214, and 255 and used an amplitude cutoff of 3750 ADUs ($\sim$ 15 keV). Fortunately, these parameters allowed the different datasets to be analyzed in a consistent way on the ground by applying the most common selection criteria for astrophysical applications of ASCA g02346 and $0.3 < E < 10.0$ keV. We will specify throughout the paper when these selection criteria are used and when the "total

Table 1. **Observations Used in this Analysis**

OBSID	Start (GMT)	Stop (GMT)	CCDs On	Event Rejection	FP Temp (C)
1057	228:17:00	228:17:42	I2,I3,S1-S4	reject g7	-99.5
1058	228:17:57	228:18:28	I2,I3,S1-S4	reject g7	-99.5
1059	228:18:43	228:19:15	I2,I3,S1-S4	reject g7	-99.5
1060	228:19:30	228:20:01	I2,I3,S1-S4	reject g7	-99.5
1061	228:20:16	228:20:47	I2,I3,S1-S4	reject g7	-99.5
1062	228:21:02	228:21:34	I2,I3,S1-S4	reject g7	-99.5
1266	228:22:58	229:01:56	I2,I3,S1-S4	reject g7	-99.4
303	286:05:58	286:09:46	I0-I3,S2,S3	reject b24,66,107,214,255 amp > 3750 ADUs	-109.2
965	287:15:49	287:20:07	I1,I3,S2-S5	reject b24,66,107,214,255 amp > 3750 ADUs	-109.0
804	008:01:01 (Y2000)	008:13:14 (Y2000)	I3,S1-S4	reject b24,66,107,214,255 amp > 3750 ADUs	-109.1

event" rate, which is everything the CCD and electronics can record and telemeter, is used. Additionally, the ACIS focal plane temperature was changed once over the course of these observations from ~ -100 C to ~ -110 C. This is significant because the number and intensity of hot pixels on the BI CCDs is a strong function of temperature. In order to allow a consistent comparison between the data at the two different temperatures, the list of hot pixels appropriate for the -100 C data were excluded from all the datasets.

2.2. The Sample Observations

We summarize four cases of extremely high background below during which CXO's position with respect to the radiation belts was distinct. The analysis of these observations spurred a re-examination of the predicted entry and exit times from the radiation belts provided by the CXO mission scheduling SW. This issue is discussed in detail in an SPIE paper by Virani et al. (2000). We include one final case in which the background was more typical.

CASE I, Exiting the Belts, OBSIDs 1057-1063: The CXO outer cover was opened at GMT1999:224:18:00. The following orbit was used to test the pointing and maneuvering capabilities of the spacecraft. The satellite then began conducting normal check out activities such as acquiring data necessary to determine the best focus position. OBSIDs 1057-1062 were focus measurements which began at GMT1999:228:17:00 just after a perigee passage at GMT1999:228:11:53. Thus, CXO was just emerging from the radiation belts with an altitude of less than 60,000 km when these observations commenced. Figure 1 shows the total ACIS S3 (the BI CCD at the focal position in the spectroscopy array) count rate and the EPHIN E150 rate for this time period. The ACIS rate has been averaged over 32.4 s intervals to better match the EPHIN integration times of 65.6 s. The quiescent ACIS rate for these observations is ~ 10 cts s^{-1}, while there are large excursions up to ~ 300 cts s^{-1}. OBSID 1057 (the first group of data in the figure) was most likely affected by the edge of the radiation belts. However, OBSIDs 1059 and 1060 are outside of what are

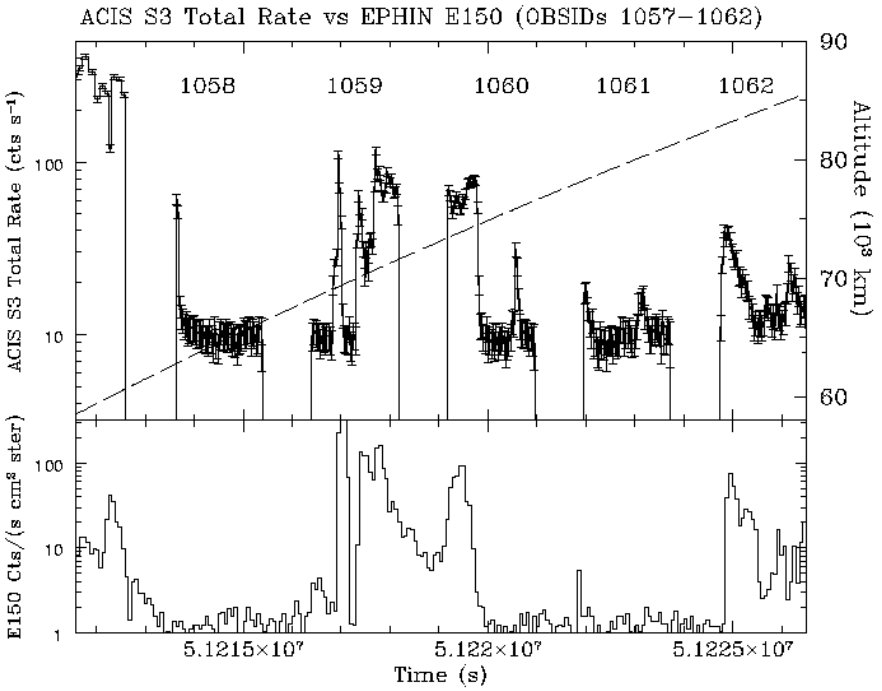

Figure 1. OBSIDs 1057-1062: The ACIS S3 total rate averaged over 32.4s intervals and the EPHIN E150 rate in the nominal integration time of 65.6 s. The units of time are seconds since 1998 Jan 1. The first group of data at the left of the plot are from OBSID 1057. The *CXO* altitude is plotted as the dashed line and labeled on the right axis.

typically considered to be the radiation belts. The ACIS rate typically increases when the E150 rate increases and the ACIS rate is constant when the E150 rate is constant. However, note that the relative increase in the ACIS rate compared to the E150 rate is different for the event at the beginning of the plot during OBSID 1057 than it is for the event beginning at $t = 5.1217 \times 10^7$ s and lasting until $t = 5.1221 \times 10^7$ s. So clearly, the E150 channel is not a complete indicator of all the particles which are capable of producing enhanced background in ACIS. We explored the correlation with the higher energy electron channels and the lowest-energy proton channel but found that the ACIS rate appeared to correlate best with the E150 channel.

CASE II, Entering the Belts, OBSID 303: OBSID 303 presents an analogous situation to CASE I above except that CXO was entering the radiation belts. The ACIS and EPHIN data from this observation are plotted in Figure 2. Significant fluctuations in the ACIS count rate are seen throughout almost the entire time interval with large events at $t = 5.6186 \times 10^7$ s and the end of the observation starting at $t = 5.6191 \times 10^7$ s. Presumably the enhanced rates at

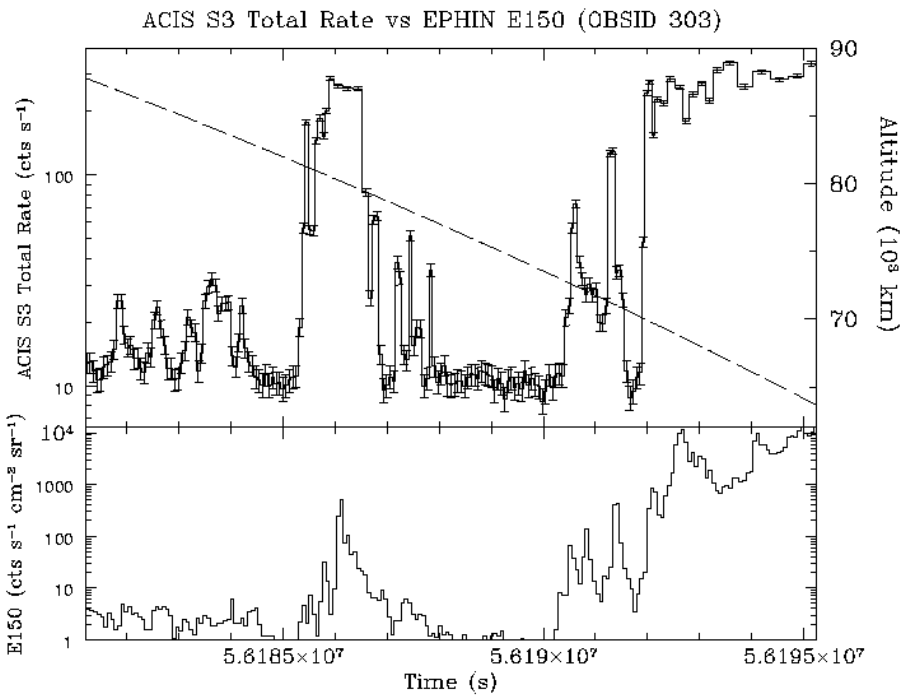

Figure 2. OBSID 303: The ACIS S3 total rate averaged over 64.8s intervals and the EPHIN E150 rate. The units of time are seconds since 1998 Jan 1. The *CXO* altitude is plotted as the dashed line and labeled on the right axis.

the end of the observation are due to the outer edges of the belts as the altitude decreased to less than 60,000 km but the earlier event is still quite far from the belts with an altitude of $\sim 80,000$ km. The large excursions above 100 cts s^{-1} caused telemetry saturation in ACIS. These two large events were also correlated with the higher-energy electron channels and the low-energy proton channel of EPHIN.

CASE III, 11 hr after perigee, OBSID 1266: OBSID 1266 was performed in the same orbit as OBSIDs 1057-1062 although at a later point in the orbit. The lightcurve of this observation is plotted in Figure 3. Once again almost the entire observation is affected by an enhanced background rate accompanied by significant fluctuations in the E150 rate. However, the ACIS rate did not increase as much as in the previous observations, always staying below 100 cts s^{-1}. CXO was at 95,000 km and ascending during this observation, yet the enhanced background persisted throughout the entire observation. This observation demonstrates the spatial extent of the particles producing the enhanced background.

CASE IV, near apogee, during a Coronal Mass Ejection, OBSID 965: OBSID 965 was performed near apogee while CXO and its environment

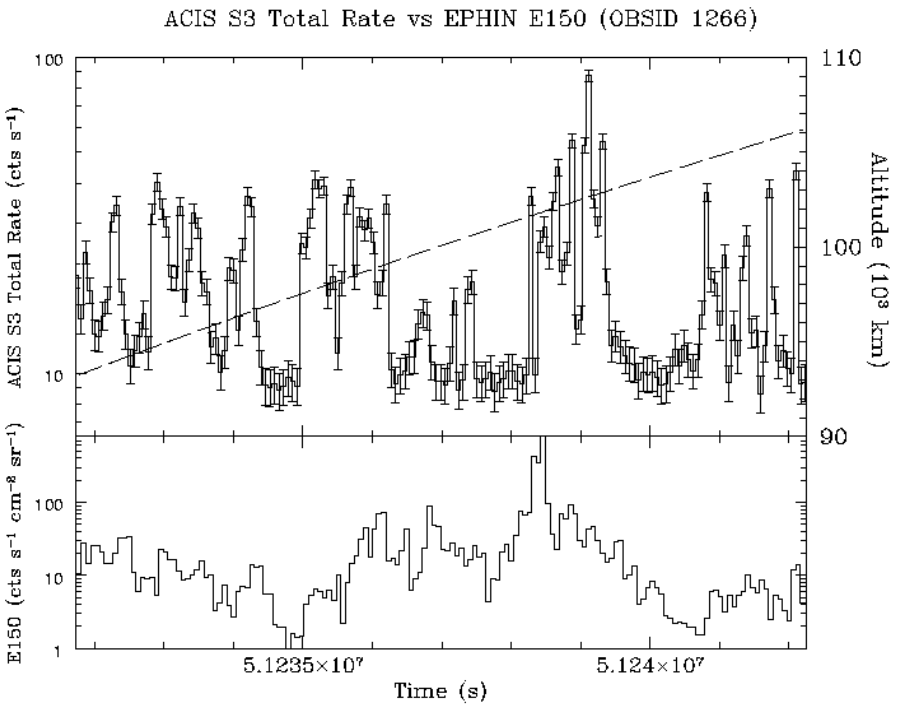

Figure 3. OBSID 1266: The ACIS S3 total rate averaged over 64.8s intervals and the EPHIN E150 rate. The units of time are seconds since 1998 Jan 1.

were subjected to the aftermath of a Coronal Mass Ejection (CME) event on the Sun. EPHIN exhibited a prolonged period of enhanced count rates in most of its channels. The ACIS and EPHIN data are plotted in Figure 4. The ACIS rate is rather quiet during this interval (except for a few small enhancements) while the E150 rate is increasing steadily throughout the observation. The spike in the ACIS rate at $t = 5.6315 \times 10^7$ s was an instrumental effect and had nothing to do with the background rate.

CASE V, near apogee, low solar activity, OBSID 804: We have presented the most pathological cases of enhanced background identified so far in the CXO mission. The cases presented so far are the exception and not the rule. As a counter example we present OBSID 804 which was acquired near apogee while the solar activity was low. The ACIS and EPHIN rates, shown in Figure 5 are low and constant throughout the majority of the observation. The only exception is a small time interval near the end of the observation at $t = 6.372 \times 10^7$ s during which the ACIS S3 rate increases just slightly above 10 cts s^{-1}.

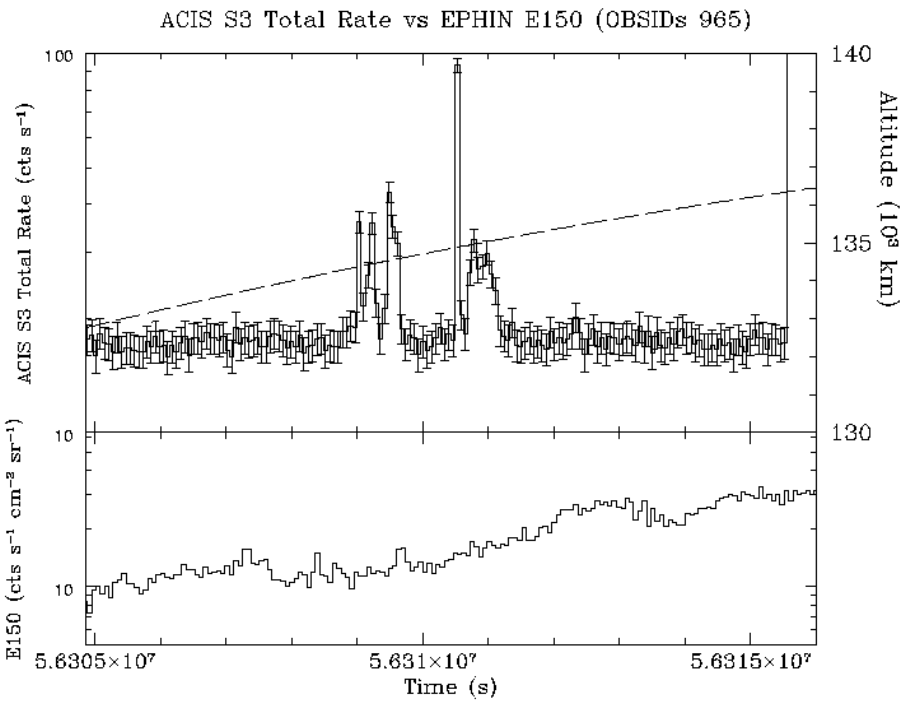

Figure 4. OBSID 965: The ACIS S3 total rate averaged over 64.8s intervals and the EPHIN E150 rate. The units of time are seconds since 1998 Jan 1. The spike in the ACIS rate at $t = 5.6315 \times 10^7$ s was an instrumental effect.

2.3. Detailed Correlation between ACIS and EPHIN

All five of the preceding cases indicate that there is a general correlation between the background rate as seen by ACIS and the EPHIN E150 channel. This is no surprise, the CCDs are sensitive to electrons in this energy range. One might hope to use the E150 channel to model and estimate the ACIS background rate. Unfortunately, the detailed correlation between the two rates is not good. We generated a simple scatter plot of the ACIS rate and the E150 rate. At this point we have restricted our event selection to events with grades of ASCA g02346 and energies of 0.3<E<10.0 keV since those are the events observers would be most interested in modeling the background. Figure 6 shows the poor correlation between the two rates. It is clear that when EPHIN shows enhanced rates, ACIS will also exhibit enhanced rates at roughly the same time. But Figure 6 shows that the exact times of the increases in the two detectors do not correspond well. Certainly, the ACIS rate cannot be described by a simple function of the E150 rate. Perhaps this indicates the process by which the electrons which EPHIN is sensitive to make their way to the focal plane is rather complex. If one believes that the low energy particles are propagating down the optical path of the telescope to the focal plane, one could easily imagine that spacecraft

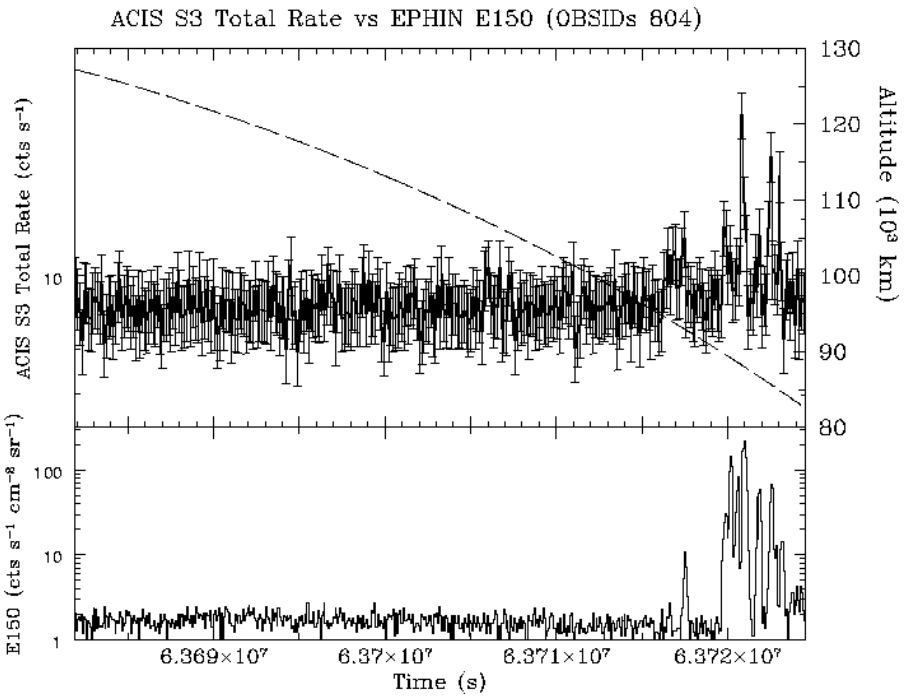

Figure 5. OBSID 804: The ACIS S3 total rate averaged over 64.8s intervals and the EPHIN E150 rate. The units of time are seconds since 1998 Jan 1.

orientation would be an important parameter in determining the possibility that particles which EPHIN is detecting can actually make it to the focal plane.

3. Detailed ACIS Characterization

3.1. BI CCD vs FI CCD

Up until this point we have shown lightcurves of BI CCD data only. The FI CCDs do exhibit enhanced background, albeit not as dramatic as the BI CCDs. For example, we plot in Figure 7 the lightcurve of the g02346, 0.3<E<10.0 keV events for the S2 (FI) CCD and the S3 CCD. The two CCDs show enhanced background during the same time intervals, but the signal is smaller in the FI CCD. This suggests that low-energy particles are mostly responsible for the enhanced background, since the particles must travel through the gate structure of the FI CCDs in order to produce a detectable signal. Ground measurements on ACIS flight-like CCDs indicate that protons must have an energy of at least 75 keV to penetrate the gate structure (see Bautz et al. 2000 and Prigozhin et al. 2000). Simulations by Kolodziecjzak et al. (2000) indicate that it is plausible

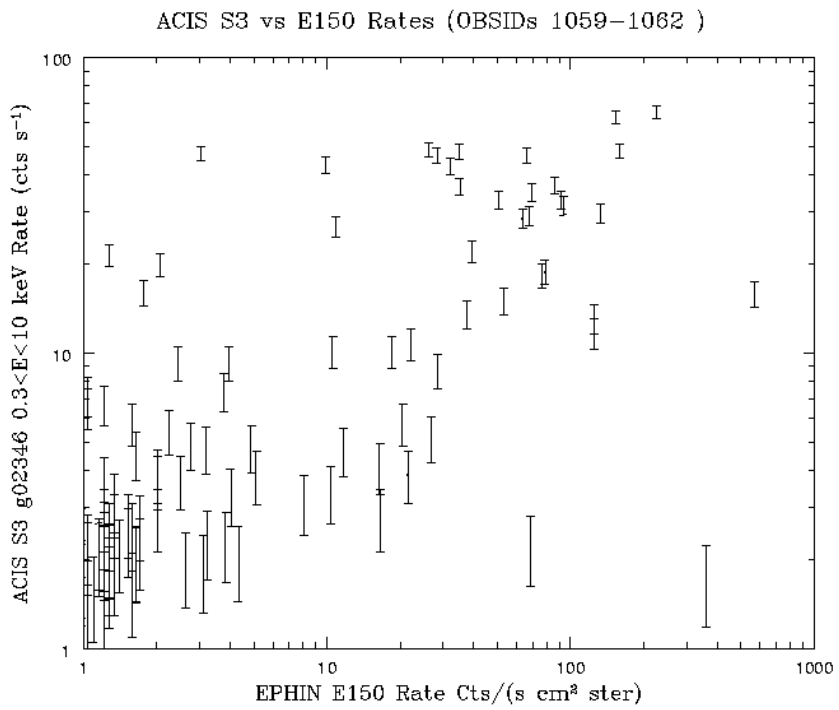

Figure 6. The ACIS S3 g02346 0.3<E<10.0 keV rate plotted versus the E150 rate for OBSIDs 1057–1062. The detailed correlation is not as good as one might have expected from Figure 1

that 100 keV protons could scatter off of the CXO's mirrors with sufficient efficiency to produce a detectable signal in the focal plane.

3.2. BI CCD vs BI CCD

Since there are two BI CCDs in ACIS, one on-axis (S3) and the other off-axis (S1), one could hope to use the off-axis BI CCD to understand the background of the S3 CCD where presumably the source of astrophysical interest lies. Comparing the lightcurves of the two BI CCDs for OBSIDs 1057-1062, it is clear the two CCDs are responding in a similar manner to the background enhancements. The S3 and S1 rates are plotted in Figure 8 and show that the correlation is excellent. The best-fit line with a reduced χ^2 of 2.34 is also plotted on the graph. The intercept is non-zero and positive. This is most likely due to some "warm" pixels on the S1 CCD which have not been excluded. These data were acquired with the focal plane at ~ -100 C and the S1 CCD shows substantially more hot pixels than the S3 CCD. We have excluded the pixels which produced an event in 50% or more of the frames, but it is probably the lower frequency warm pixels which are causing the offset. The slope of 0.847 indicates that the count rate on S3 is almost always higher; this would be consistent with a higher particle flux on-axis.

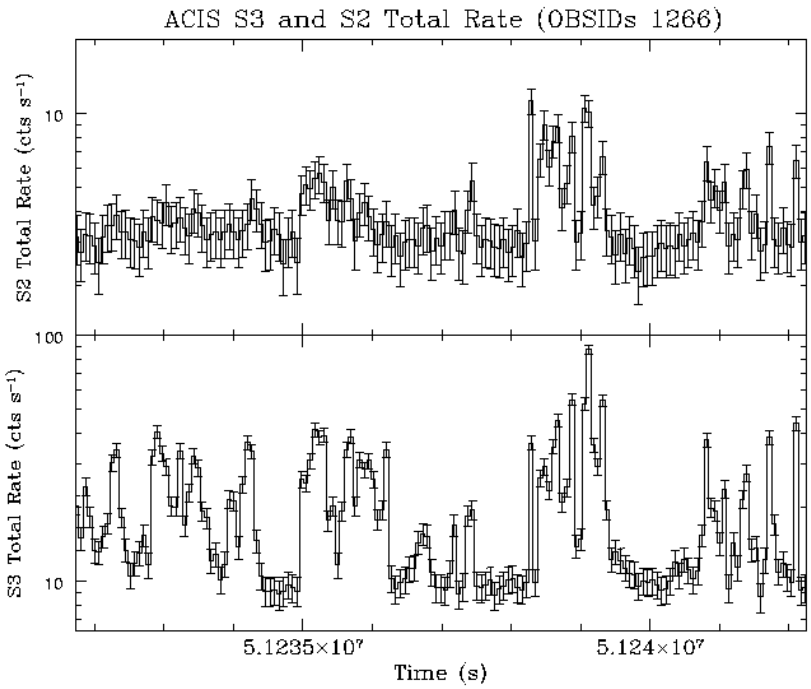

Figure 7. The ACIS g02346 0.3<E<10.0 keV rate of the S2 and S3 CCDs for OBSID 1266. Note how the two detectors show enhanced count rates in the same time intervals but the enhancement is much smaller in the FI CCD.

3.3. Spatial Distribution

We examined the spatial distribution of the events associated with the periods of enhanced background by making an image in detector coordinates when the background rate was high and an image when the background rate was low and subtracting the two. We selected the time periods in OBSID 303 from $t = 5.6188 \times 10^7$ s to $t = 5.6190 \times 10^7$ s as the "low background" period and two time intervals from $t = 5.61855 \times 10^7$ s to $t = 5.6186 \times 10^7$ s and from $t = 5.6192 \times 10^7$ s to $t = 5.6195 \times 10^7$ s as the "high background" periods. For this analysis we selected events with grades of *ASCA* g02346 and amplitudes between 0.3<E<10.0 keV. A point source detection algorithm was run on the data and point sources were excluded from both the high and the low background datasets. There was a galaxy on-axis on the I3 CCD so there is sparser coverage on-axis after the point source removal. We corrected the two datasets for the different exposure times and subtracted the images. The resulting image is displayed in Figure 9. The selected colorscale indicates the highest intensity as white and the lowest intensity as black. The data have been binned into 32×32 pixel regions. The I1 CCD is in the upper left corner and appears to receive the highest flux of these excess counts. The distribution is not azimuthally

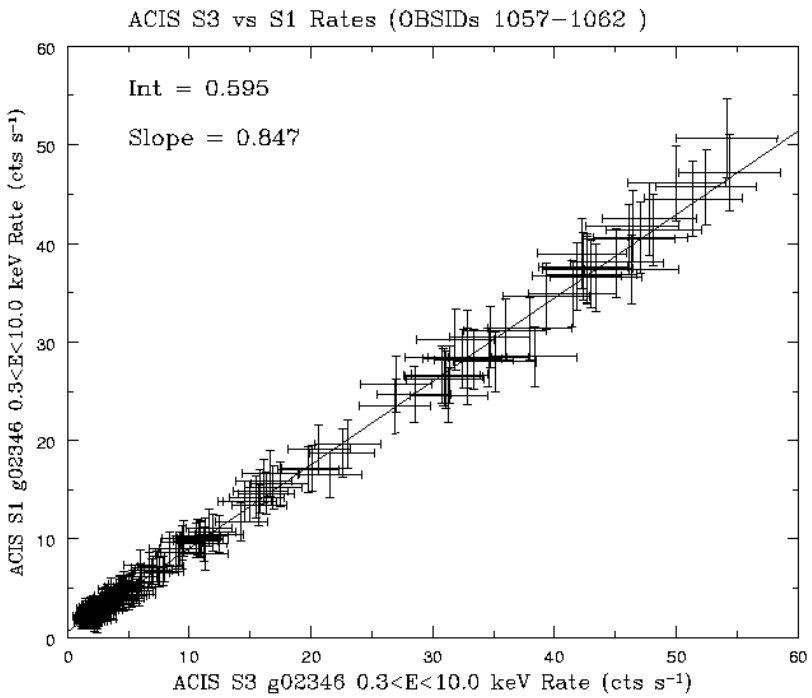

Figure 8. The ACIS g02346 0.3<E<10.0 keV rate for the two BI CCDs (S1 & S3) plotted against each other for OBSIDs 1057–1062. The correlation is excellent with a best-fit line giving an intercept of 0.595, slope of 0.847 and a reduced χ^2 of 2.34

symmetric. The radial profile of these events is plotted in Figure 10. The "high background" data exhibit a radial dependence which might be consistent with the vignetting pattern of the telescope. However, once the "low background" data are subtracted from the the high background data the distribution is actually depressed on-axis. This is difficult to explain with simple scattering off of the mirrors.

The distribution on S3 is even more peculiar. We used the high and low background data from OBSIDs 1057–1062 to generate an image of the excess counts in detector coordinates in the same way as we did for the I array CCDs in OBSID 303. The resulting distribution on S3 appears as a band of higher intensity running across the middle of the CCD in the long direction of the S array, with lower intensity near the top and bottom of the CCD (near the framestore). This distribution also can not be explained by simple scattering off of the mirror.

3.4. Spectral Distribution

We used OBSID 303 to extract information on the spectral distribution of the excess events in the FI and BI CCDs. We once again extracted spectra from

the periods of "high background" and from the period of "low background" in OBSID 303. We then subtracted the two spectra for each CCD in order to get a spectrum of the excess events. The result for the I3 and S3 CCDs is plotted in Figure 11. The spectra were generated from *ASCA* g02346 events. Notice that the excess counts extend across the entire bandpass from 0.3 to 10.0 keV, which is what is typically used for astrophysical observations. The signal is much higher in the BI CCD as expected. The spectrum cannot be well fitted with a simple power-law plus a constant model. We intend to explore more complex models in the future. It is unfortunate that the excess counts extend across the entire bandpass, but it will be simpler to subtract a smooth background spectrum for most astrophysical applications. The variability of this background spectrum from observation to observation still needs to be explored.

3.5. Impact of High Background Events on Observations

As the previous sections have shown, the events associated with the enhanced background times reproduce many of the characteristics of valid X-ray events in the ACIS CCDs. Typically one attempts to distinguish background events from X-ray events of interest by their different grade or pulse-height distributions. Neither of these techniques will be successful with the background events we have examined here. We recommend that CXO guest observers always generate a lightcurve from their observation and examine it for enhancements. If the time intervals represent a small fraction of the observation, it may be best to exclude those times. If the fraction of time is non-negligible and the source is a point source, the GOs should consider subtracting this background in the same way they subtract the quiescent background. If the object is a large extended object, the GOs should consider using data from another CCD as the background data. For example, the S1 CCD should be tried as the background source for the S3 CCD and one FI CCD could be used as the background source for another FI CCD.

GOs should also be aware of the impact of high background times on telemetry saturation. Most of the observations presented in this paper saturated the telemetry stream significantly and therefore data were lost. Since the BI CCDs are significantly more susceptible than the FI CCDs to these background enhancements, observations which utilize one or both BI CCDs should be carefully planned. The GO may wish to utilize more aggressive on-board filtering to throttle back the event rate. For example, Table 2 shows the effectiveness of various combinations of event filters on the OBSID 303 data. Simply lowering the upper event amplitude cutoff from 15 keV to 10 keV or even 8 keV may provide enough reduction in the overall count rate to prevent telemetry saturation.

4. Future Work

We intend to continue to examine the correlation between the ACIS count rates and EPHIN count rates, although a preliminary examination indicates that a correlation good enough to allow modeling of the ACIS background may not exist. We hope to utilize the the newly-developed *Chandra Radiation Model* (see Blackwell et al. 2000) which will provide a more accurate description of the particle environment between the radiation belts and the magnetosphere.

Table 2. **Effectiveness of Event Filtering on Telemetry Saturation**

Event Selection	# of Events	Rate (cts s^{-1})
S3 (BI CCD)	(11305.6s)	
g02346, 0.3<E<10.0 keV	336210	29.74
g02346	466780	41.29
0.0<E<8.0 keV	334143	29.56
0.0<E<10.0 keV	400280	35.40
b24,66,107,214,255, E<15 keV	608458	53.82
S2 (FI CCD)	(11948.8s)	
g02346, 0.3<E<10.0	60146	5.03
g02346	116315	9.73
0.0<E<8.0	140960	11.80
0.0<E<10.0	157554	13.19
b24,66,107,214,255, E< 15 keV	220023	18.41

We also hope to explore a correlation with the low-energy electron and proton channels of the *Advanced Composition Explorer* (ACE) satellite which CXO is currently using as an early warning of particle storms emanating from the Sun. The detailed CCD characterization needs to be expanded to datasets which provide higher statistical precision. The spatial distribution of the excess events hinted at in this paper needs to be confirmed by observations with a larger number of counts and with the focal point of the telescope on the imaging and spectroscopy arrays. The spectral distribution of the the excess events in the BI and FI CCDs needs to be determined to better precision and the differences between the two types of detectors needs to be understood. Presumably, the spectrum observed by the ACIS CCDs will change as the spectrum of the incident particles changes. This would be the most likely explanation of the cases in which the BI CCDs exhibit an enhanced count rate but the FI CCDs show little or no enhancement; the spectrum of the incident particles may be too soft to produce a signal in the FI CCDs. Finally, new techniques must be explored for identifying, excluding, and/or modeling the background counts in order to recover a larger fraction of the useful observation time.

5. Acknowledgments

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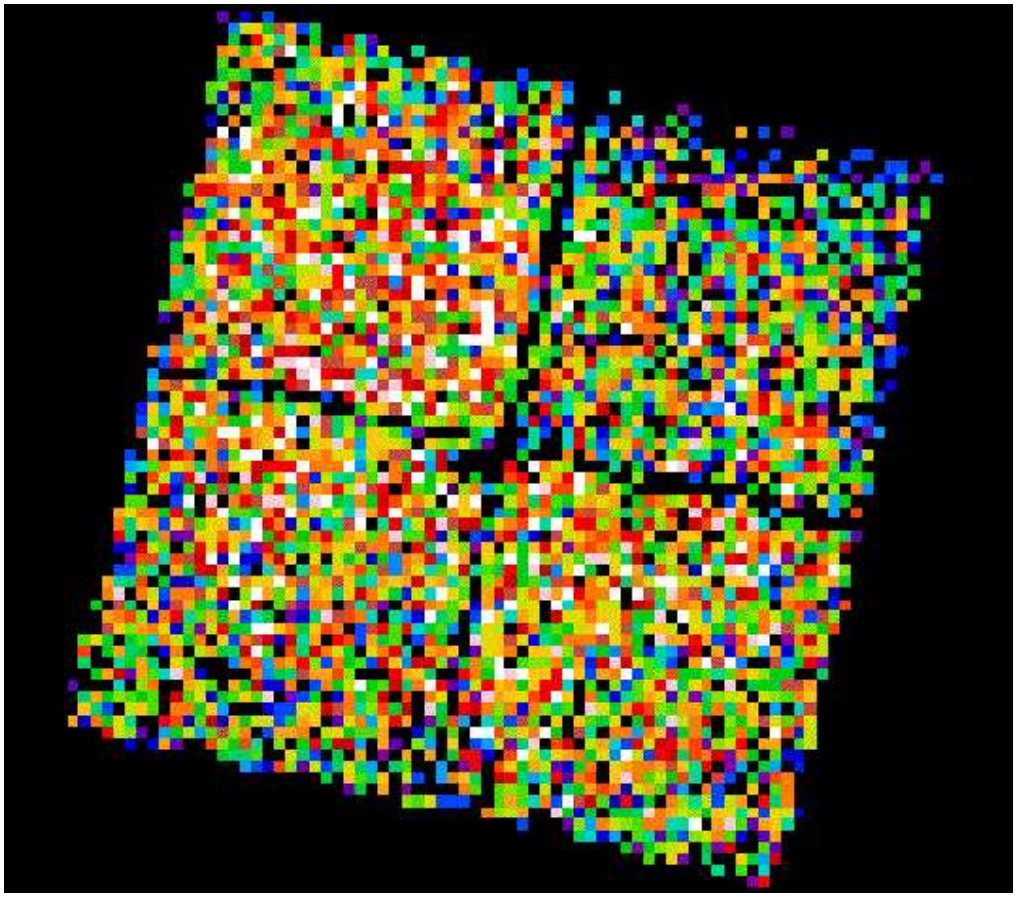

Figure 9. The difference of the observed spatial distribution of counts between the high background periods and the low background periods of OBSID 303. In the chosen colorscale white indicates the highest intensity and black indicates the lowest intensity. Events were selected with grades of g02346 and with amplitudes 0.3<E<10.0 keV. The I3 CCD with the HRMA aimpoint is the lower-left detector. I0 is the upper right, I1 is the upper left, and I2 is the lower right detector.

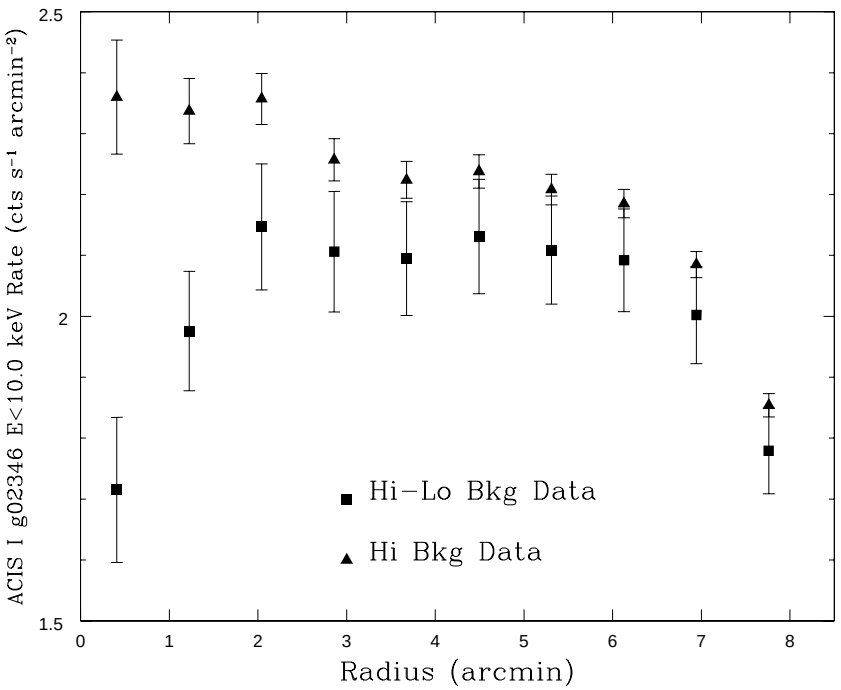

Figure 10. The radial profiles of the high background periods and the high-minus-low background periods for OBSID 303. Events were selected with grades of g02346 and with amplitudes 0.3<E<10.0 keV. Notice that the radial profile of the so-called "excess" events is actually lower on-axis than off-axis.

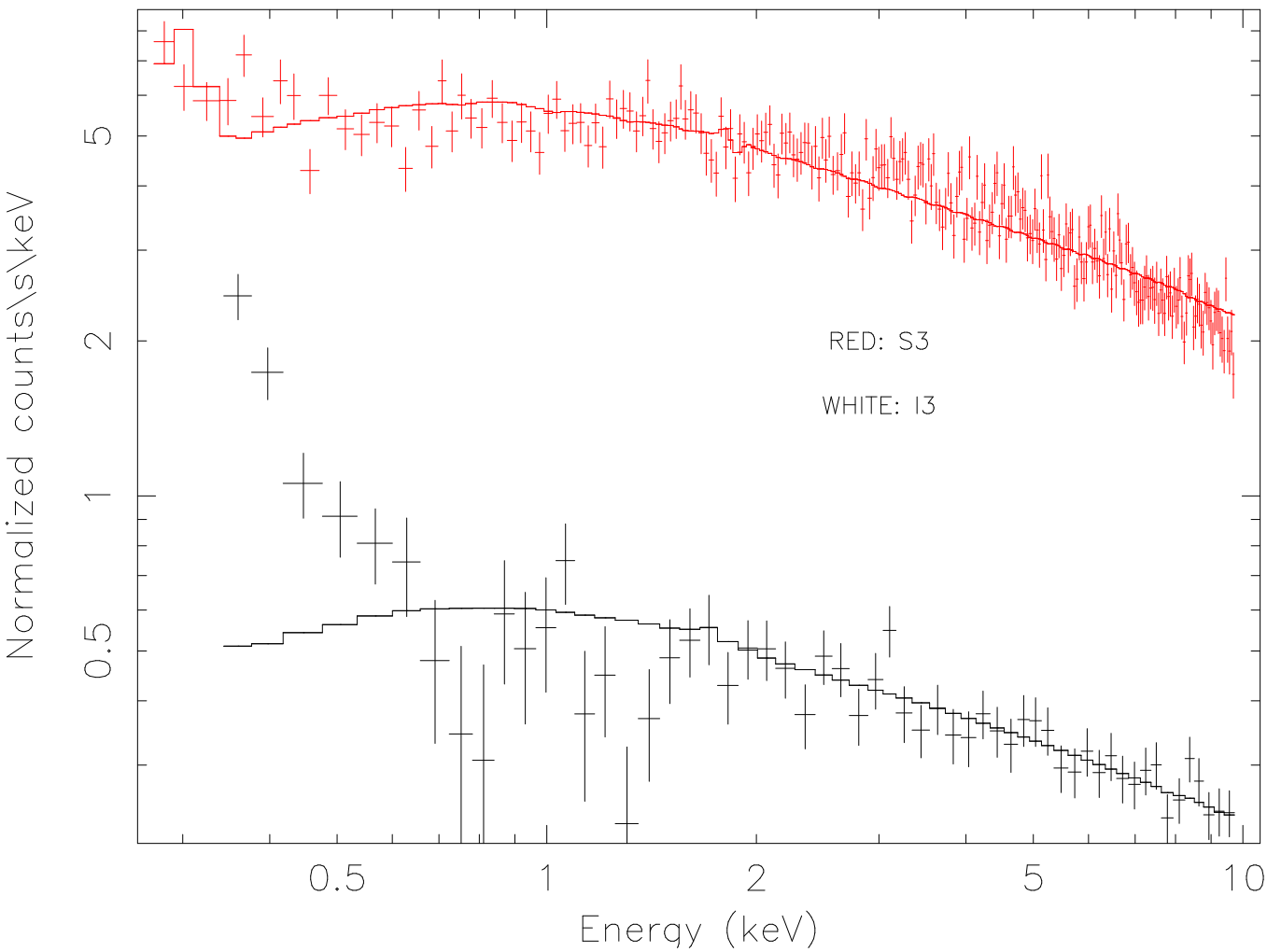

Figure 11. The spectrum of the excess background counts in the S3 and I3 CCDs for OBSID 303. Only g02346 events were selected for these spectra.