Monitoring the Charge Transfer Inefficiency of ACIS and the Impact of the Varying Cosmic−Ray Background

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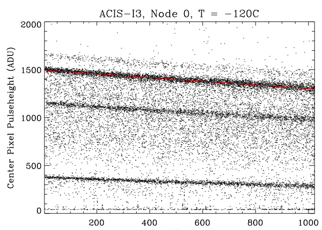
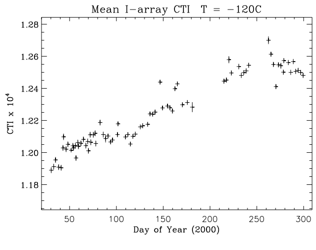
Abstract

Soon after launch, the Advanced CCD Imaging Spectrometer (ACIS), one of the focal plane instruments on the *Chandra X-ray Observatory*, suffered radiation damage from exposure to soft protons during passages through the Earth's radiation belts (Prigozhin et al. 2000). Since mid-September 1999, ACIS has been protected during radiation belt passages and there is an ongoing effort to prevent any further damage particularly from coronal mass ejections or other geomagnetic activity. Monitoring the charge-transfer inefficiency (CTI) of the CCDs using observations of the ACIS External Calibration Source can be an effective tool to detect any change in performance, however this measure and the instrument performance are also dependent on the total amount of charge deposited onto the CCD, which is dominated by cosmic rays. An increasing rate of cosmic ray hits will reduce the number of electron trap vacancies and thus decrease the measured CTI. We report on efforts by the ACIS Instrument team to understand and quantify the influence of the cosmic ray background on the measured CTI of the ACIS CCDs. We also report on attempts to remove the variation due to the background component from ACIS CTI measurements in order to more effectively monitor the health of the instrument.



Measuring Charge Transfer Inefficiency

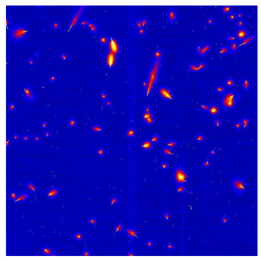
A symptom of radiation damage in CCDs is an increase in the number of charge traps. When charge is transfered across the CCD, some portion can be captured by the traps and re-emitted later. If the original charge packet has been transfered away before the traps re-emit, the captured charge is "lost" to the charge packet. This can be seen in the figure, which shows pulseheight versus row number for each photon in a dataset taken with ACIS-I3 and the External Calibration Source. The pulseheight of each spectral line drops with increasing transfer distance. Charge Transfer Inefficiency or CTI is defined as the fractional charge loss per pixel at a given energy and is calculated from a linear fit to the pulseheight versus row number; CTI = (slope/intercept).



ACIS CTI Measurements

Since the discovery of the radiation damage, a continuing series of observations have been undertaken just before and just after the instruments are safed for perigee passage to monitor the CTI of the ACIS CCDs. ACIS is placed in the HRC-S position exposing the CCDs to the External Calibration Source which produces many spectral lines including Mn-Kα (5.9 keV). The data are taken in the standard Timed Exposure mode with a 3.2 second exposure time. Typical exposure times range from 5.5 to 8 ksecs. Occasionally a standard CTI measurement is replaced by an ACIS diagnostic or engineering test and in certain seasons and satellite geometries the focal plane temperature is higher than the nominal. In both cases the CTI measurement is not used for monitoring purposes.

The figure shows the mean CTI of the I-array at 5.9 keV for all nominal CTI measurements taken by ACIS since the focal plane temperature was lowered to -120 C on 30 January 2000. Typical errors are around 2×10^{-7} (0.2%) so the scatter and structure seen are primarily real. There is an apparent secular increase in the measured CTI of 2.4×10^{-8} / day or 8.7×10^{-6} / year, about 7%. The standard deviation about a purely linear increase is 6×10^{-7}, three times larger than the measurement errors. All the front-illuminated (FI) CCDs show a similar increase. The two back illuminated (BI) CCDs are more protected from low energy protons and show little to no change in CTI since launch.



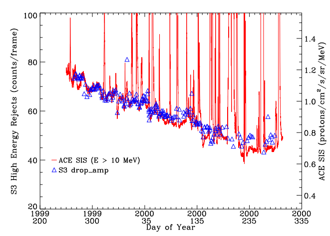
Sacrificial Charge and the Cosmic Ray Background

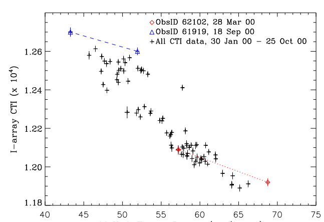
It has been shown that measured CTI is a function of X-ray fluence or, more specifically, the amount of charge deposited on the CCD (Gendreau et al. 1993). As the fluence increases, traps filled by one charge packet may remain filled as a second charge packet is transferred through the pixel. The second charge packet sees fewer unoccupied traps as a result of the previous "sacrificial charge". On a larger scale, the measured CTI is reduced.

In *Chandra's* high altitude orbit, cosmic rays account for a large fraction of the charge deposited on the CCDs. This can be seen in the above image, a single raw frame from early in the mission. If the cosmic ray background rate were changing, one would expect to see the changes reflected in the measured CTI of the FI CCDs. Shown below is the counting rate of events on the BI CCD S3 with pulseheights greater than 3750 ADU during all nominal CTI measurements. This pulseheight corresponds to an energy of $\sim$ 15 keV so we believe these events to be a result of cosmic rays and not X-rays. These events are rejected and not telemetered by the flight software except in the exposure records (the 'DROP_AMP' field in *_stat1.fits). Using S3, which is relatively unaffected by low-energy protons that damage the FI devices, should remove any radiation damage induced structure in the amplitude rejection rate.

Also plotted below is an hourly average of the flux of protons with E > 10 MeV measured by the Solar Isotope Spectrometer (SIS) on the ACE spacecraft. ACE is located at the Sun-Earth L1 point and thus sees many solar proton flares that ACIS does not, however overall the two rates are well correlated. During solar quiet times, SIS rates are dominated by low-energy cosmic rays. The S3 reject rate is therefore a reasonable measure of the cosmic ray rate incident on the CCDs.

The cosmic ray background measured by ACE and ACIS has been decreasing since *Chandra's* launch. This decrease is due to the increase of magnetic field strength in the heliosphere associated with the 11-year solar cycle. Once solar maximum is passed, the ACIS cosmic ray background should level out and begin to increase. The most recent ACIS and ACE data may indicate that this background trend has reversed, but more data are needed for confirmation.

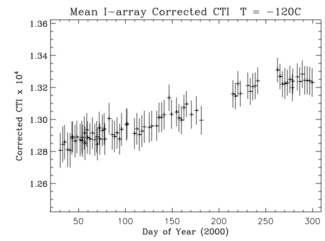




Anti-correlation of CTI with Background Rate

Based on our knowledge of the action of sacrificial charge on measured CTI and the currently decreasing cosmic ray background, we expect that some of the increase in measured CTI is due to the changing background and not to intrinsic increases in detector radiation damage. The above figure shows the anti-correlation of CTI and the S3 high energy reject rate. Since the background rate has only trended downward thus far in the mission there is a degeneracy between increase in CTI from decreasing sacrificial charge and increase in CTI from further radiation damage to the CCD. We expect the background rate to begin increasing at some point after solar maximum and will revisit this problem at that point.

In order to break this degeneracy, two CTI measurements were taken in alternating exposure mode (also called interleaved mode) with exposure times of 3.2 and 4.0 seconds on 28 March 2000 and 18 September 2000. For each observation, since the data from the two frame times were taken simultaneously, the change in CTI represents only the sacrificial charge effect. In the above figure the red and blue points are from the 28 March and 18 September data, respectively. The two points in each color are for the two frametimes; the high CTI corresponds to 3.2 sec, the lower to 4.0 sec. The fact that the trend seen in the CTI data is steeper than that in the alternating exposure data indicates that some real change may have taken place. A linear fit to each of the alternating exposure mode tests yields a very similar slope (-1.5 ± 0.2 and $-1.2 \pm 0.3 \times 10^{-7}$ CTI / S3 High Energy Rejects) and intercepts (1.29 ± 0.02 and $1.32 \pm 0.02 \times 10^{-4}$). This slope can be used to "detrend" the CTI data and remove the sacrificial charge effect.



Monitoring ACIS CTI

In order to monitor the CTI, the effects of sacrificial charge need to be removed from the data. Using the linear correlation from above, one can "correct" the CTI measurements for the changing particle background. The resulting corrected CTI can be used to search for real changes in the CTI due to radiation damage and is shown above. The correction used is of the form

$$\text{Corrected CTI} = \text{Measured CTI} + [\text{S3 High Energy Rejects} \times \text{Detrend Factor}]$$

where the last factor is the mean slope from the two linear fits discussed earlier (Detrend Factor $= -1.4 \pm 0.2 \times 10^{-7}$ CTI/S3 High Energy Rejects).

Typical corrected CTI errors are around 9×10^{-7} (1%) and are dominated by the uncertainty in the correlation. A residual increase remains in the corrected data. If this increase is assumed to be linear, the CTI is increasing at a rate of $1.7 \pm 0.1 \times 10^{-8}$ / day or $6.2 \pm 0.4 \times 10^{-6}$ / year, about 5%, which is a little more than half the increase present in the raw CTI data. The standard deviation from a purely linear increase for the corrected CTI data is now 4×10^{-7}, much closer to the CTI measurement errors than the uncorrected CTI data.

Is ACIS CTI Increasing?

The following limits or measurements can be made on a possible CTI increase:

- Based on the measured CTI and the decreasing background:
  Δ CTI $\leq 8.7 \times 10^{-6}$ / year.
- From the intercepts of the alternating exposure mode fits:
  Δ CTI $= (5.6 \pm 4.6) \times 10^{-6}$ / year.
- From the CTI data corrected for background variations:
  Δ CTI $= (6.2 \pm 0.4) \times 10^{-6}$ / year.

Acknowledgments

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