Correction of radiation damage in the Chandra X-ray CCDs

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Frontside illuminated X-ray CCDs comprising the focal plane of the Chandra X-ray Observatory suffered from the exposure to low energy protons leaking through the telescope mirrors in the beginning of the mission. As soon as the mechanism was understood, further damage was quickly prevented by moving the instrument away from the telescope focus during the radiation belt passages. Nevertheless, accumulated damage led to the charge transfer inefficiency (CTI) and deterioration of spectroscopic properties of the CCDs. This can be clearly seen in Figure 1 showing pulse height *vs* row plot for the device illuminated by the on-board Fe^{55} calibration source.

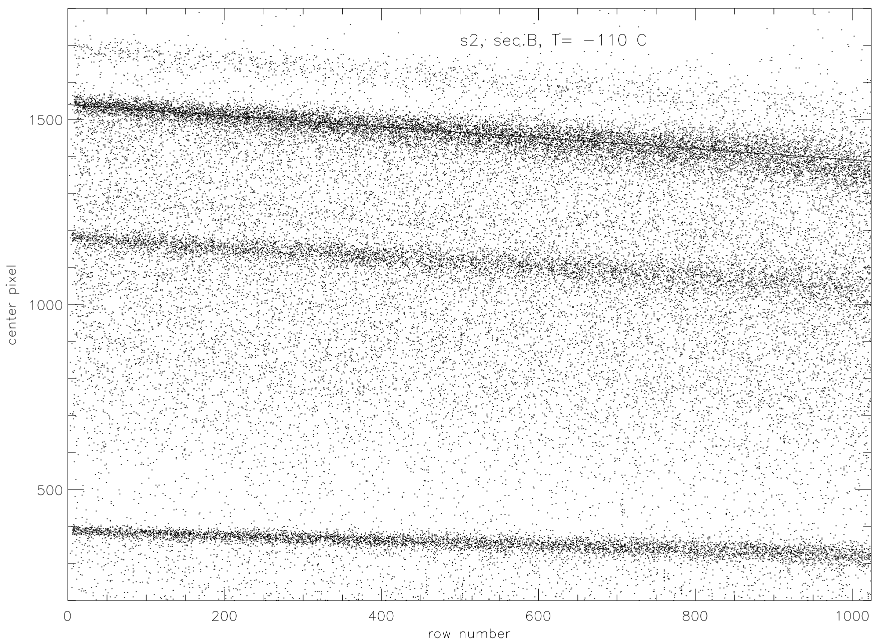

Figure 1: Pulseheight of the center pixel of and event as a function of row number at -110 C for the damaged flight device S2.

The CTI is caused by electron traps introduced into the buried channel of the CCD. These traps capture signal electrons from the charge packets and reemit them back into the subsequent pixels, creating long signal tails behind every X-ray event. Our attempts to characterize the trap parameters indicated that there are several different types of traps present with different emission time constants varying in a very wide range from tens of microseconds to seconds. The charge loss depends on the number of empty traps encountered by the charge packet and hence is a function of the distance to the previous charge packet (precursor) and its amplitude. This results in increased noise on the magnitude of the charge loss and is most damaging for the spectroscopic performance of the device implying significant increase of energy resolution at the rows near to the top of the image section (see Fig. 5).

The goal of this work was to characterize the damage and develop ways to improve the performance of the device. To achieve this we have introduced a new clocking mode of a CCD (so-called "squeegee" clocking). In "squeegee mode" several rows of a CCD move back and forth between top and bottom of the image section and are never read out. The flux of cosmic rays and X-ray photons illuminating the device generates signal electrons in these rows. Some fraction of the accumulated electrons is lost during the transfer of "squeegee rows" to filling the empty traps in the channel in the imaging section. The density of traps and the illumination intensity determine the equilibrium level of charge in these rows, which is typically on the

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order of couple of thousand electrons. "Squeegee technique" is in effect a replacement for the input diode (Chandra CCDs do not have one) which could be used to inject charge into the array.

Signal charge accumulated in the "squeegee rows" fills the electron traps in the transfer channel before the beginning of each frame. This reduces the variance of the charge loss since the traps with long enough time constants stay filled and do not contribute to the charge loss when the real signal packets arrive. Besides that, "squeegee mode" sets the same initial condition for the traps in each frame and makes it possible to calculate the charge loss for each event if all the precursors in the same column of the current frame are known. Such calculation, though, requires knowledge of the densities and time constants of the electron traps.

We have measured the trap parameters with time constants that are comparable to the parallel transfer time by fitting an appropriate functional form to the signal in the trailing pixels behind single pixel events corresponding to 5.89 keV photons. Averaging thousands of such events allowed us to reliably detect sub-electron levels of the reemitted signal as far as 30 pixels behind the center of the event (see Figure 2). Signal

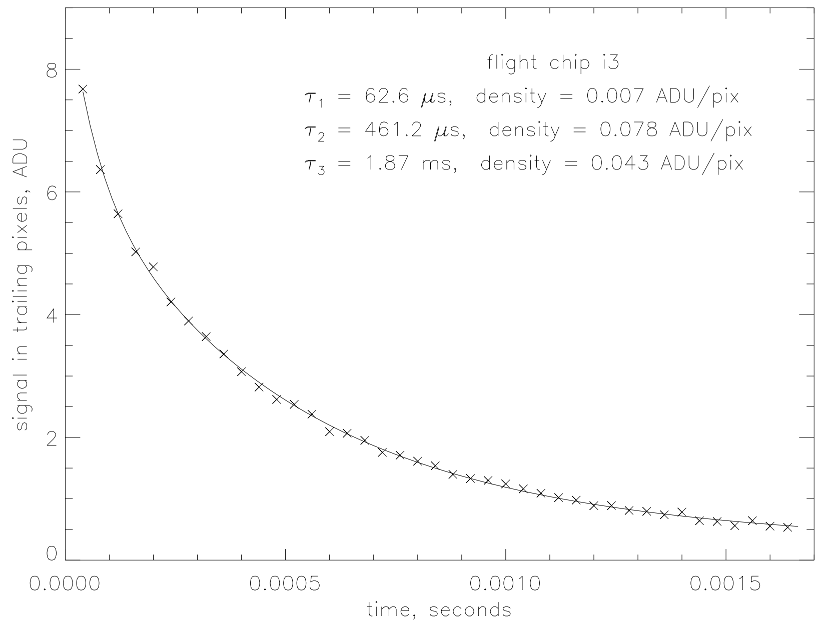

Figure 2: Amplitude of the signal in the trailing pixels behind the center of the $Mn\ K_\alpha$ event as a function of time. Solid line is a best fit to the data of the sum of the 4 exponential functions corresponding to 4 electron traps with different time constants.

amplitude in the trailing pixels is the strongest near the top of the imaging array and has to be measured there. This limits the range of the time constants measured, because it is not possible to watch the trailing pixel amplitudes more than 30–50 pixels behind the center pixel of the event.

In order to determine a trap with much longer time constant we measured trailing signal behind the "squeegee rows". Such trailing can be observed in every pixel of the imaging section, thus allowing to increase the measurement time span to entire image section transfer time (1026x40 μs). Again, averaging many columns and thousands of frames and applying a corresponding model with the fixed trap parameters found with the previous technique (the model itself is different in this case), we were able to find another trap with $\tau = 1.9\ ms$ at -120^0 C.

The most difficult task was to find the parameters of the trap with time constant comparable to the frame time (3.2 seconds). A clear evidence of the presense of the traps with very long time constants is shown on the Fig. 3. It shows center pixel amplitudes for two different groups of events. One is formed by events that do not have any other events (precursors) in the same column in front of them. For such events all traps in the channel were filled before the start of the frame integration when the "squeegee rows" were transferred from the bottom of the frame to the top. In other words, all the traps were allowed to reemit trapped electrons for 3.2 seconds (frame integration time) before the arrival of the signal charge. The second

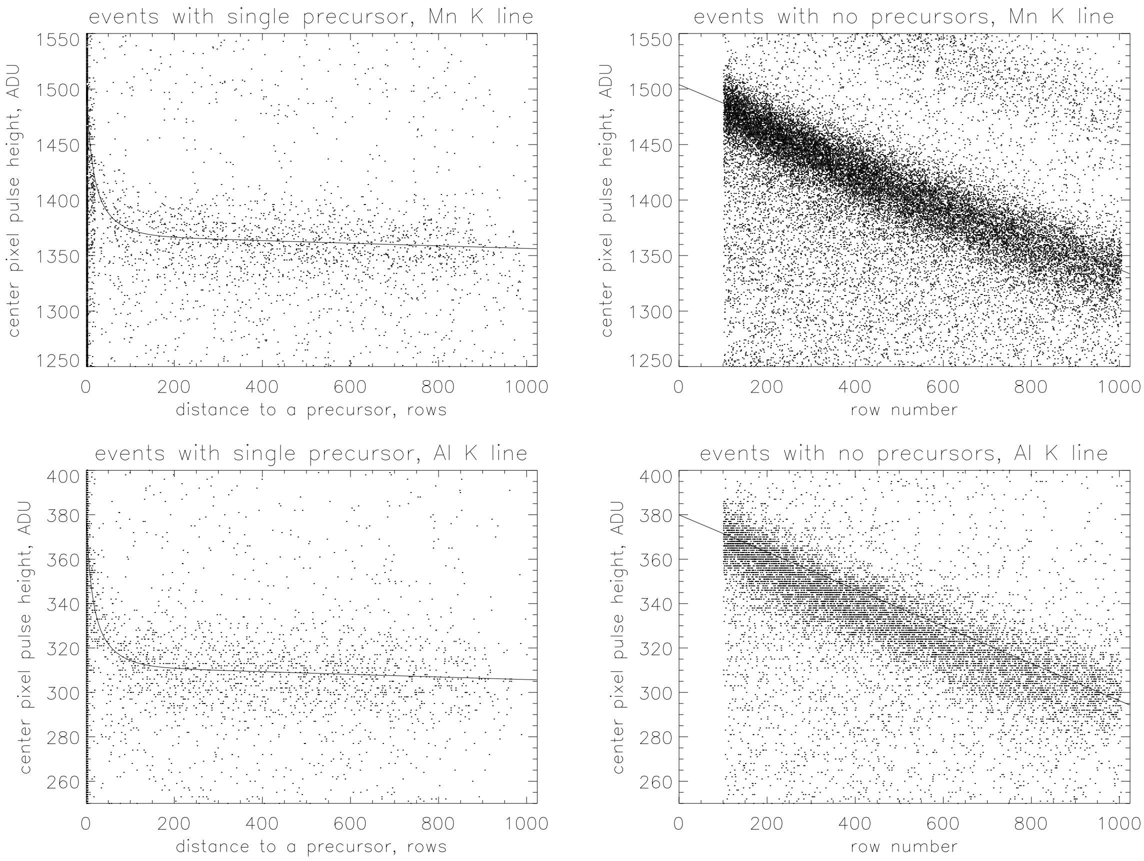

Figure 3: Plots on the left: amplitude of an event (all of them from rows above 800 and all the events have the closest precursor amplitude larger than that of the event) as a function of a distance to a precursor. Plots on the right: center pixel amplitude as a function of row number. These are events that have no precursors. Plots on the top are for $Mn\ K_\alpha$ line, plot on the bottom for $Al\ K$ line.

group is formed by the events which have only one precursor in front of them and the amplitude of the precursor is larger than the amplitude of the event itself. The plot of the event amplitude as a function of a distance to the precursor is shown on the left of the Fig. 3. Solid lines on all the plots represent the model prediction assuming four traps with different time constants. Three shorter time constants were adopted from the previously mentioned techniques. A noticeable slope of the line on the plots on the left indicates that there is a trap with much longer time constant. An important confirmation of this fact is that charge loss for the events at the top of the array with no precursors is larger than the charge loss for the events from the top with a single precursor at the very bottom of the array. A remarkable fact related to the plots of the events with no precursors (the ones on the right) is that the width of the monocromatic lines does not increase significantly at the top of the imaging section. This proves conclusively that the loss of energy resolution near the top of the array which is evident in Fig. 1 is indeed caused by the very wide range of distances to the precursors.

Analyzing signal amplitude for the monoenergetic photons as a function of row number we found that there is a significant nonuniformity in the distribution of traps along the column of the CCD. The change in the amplitude from one row to the next is caused by trapping of the electrons in a transfer between these particular rows, the rest of transfer is exactly the same for signal packets from both rows. This means that the derivative of the signal amplitude as a function of row number is a measure of the local trap density. We have been able to extract the the trap distribution from the available data, the result is shown in the Fig. 4.

We have developed a model for calculating the charge loss for any signal charge with known precursors. Incorporating the measured trap parameters into the model and applying this as an amplitude correction to all the events results in the energy resolution of 220 eV (FWHM) at 5.89 keV near the top of the image section of the CCD. This is a significant improvement over the energy resolution of 420 eV for the raw data at the same location near the top of the array (see Fig. 5).

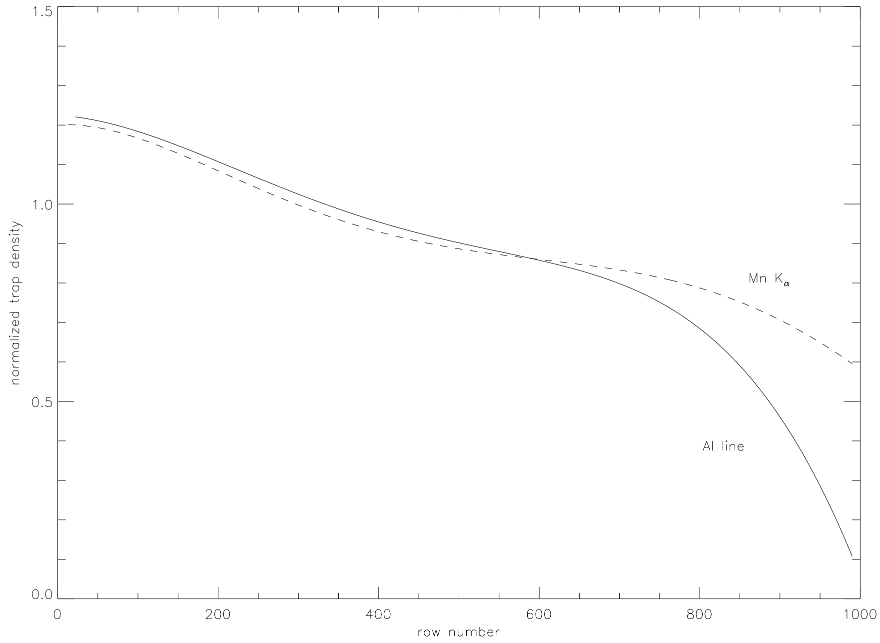

Figure 4: Relative density of traps as a function of row number measured at two different X-ray energies corresponding to $Mn\ K_\alpha$ (5.89 keV) and Al (1.49 keV) emission lines.

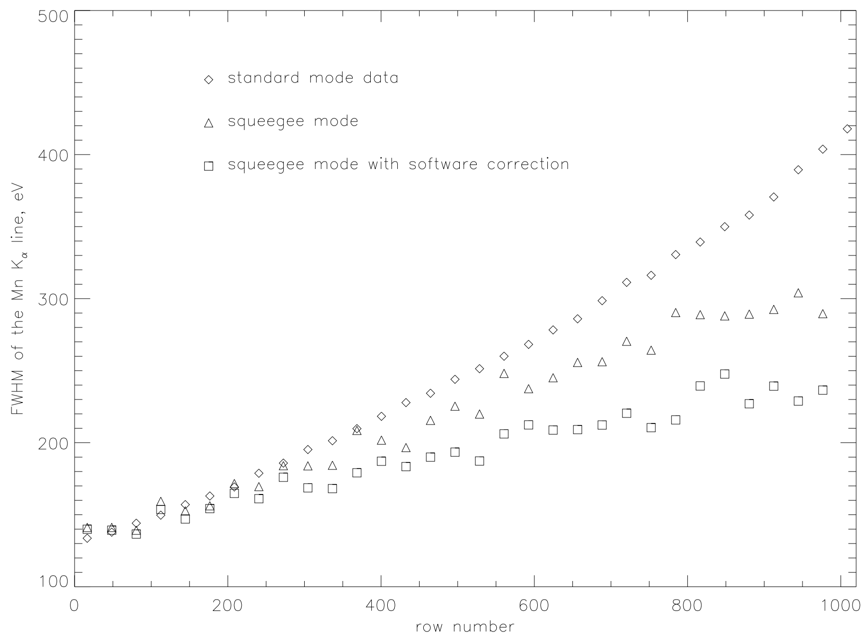

Figure 5: Energy resolution of the damaged flight CCD at $Mn\ K_\alpha$ (5.89 keV) as a function of row number.