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How CTE Affects Extended Sources

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ABSTRACT

We investigate the effect of CTE on the shape and structure of extended sources. We subtracted pairs of images of individual galaxies observed near and far from the read-out amplifier. The average profile of the galaxy residuals is distinctly asymmetric and indicates that charge is primarily lost from the amplifier-side of the galaxy image. The side of the galaxy away from the amplifier suffers little charge loss because charge traps encountered have been filled and in addition, charge is detrapping. These results are reproduced by a simple model of the read-out process.

1. Introduction

The most celebrated (and cursed) result of imperfect charge transfer efficiency (CTE) is the loss in strength of a detected source as a function of its position on the detector. Space-based observatories such as HST and Chandra are notorious sufferers of charge transfer inefficiency (CTI; CTI=1-CTE) and great effort and significant observing time has been expended to quantify the total loss to a WFPC2 charge packet as a function of the number of serial and parallel clockings, background, packet size, and detector lifetime (Whitmore, Heyer, & Casertano 1999; Holtzman et al. 1995; Stetson 1998; Saha 2000). Except for the need to continually monitor the degradation of CTE, this body of work is sufficient to provide corrections to users' measurements of point sources.

Naturally, observer requirements go beyond the accurate measurements of the fluxes from stars. The detected counts from resolved sources (i.e., galaxies, nebulae, rings, planets) extend over a greater number of pixels than point sources, and observers often need to measure the structure of these sources. For examples, measurements of galaxy parameters may include the morphology, axial ratio, positional angle, asymmetry, concentration and centroid (in addition to a magnitude). Ideally a prescription or correction formula would be available to correct these measurements for the effects of CTE.

Unfortunately, the physics of CTE is more complex than simple incomplete charge transfer. Recent investigations demonstrate that charge which fails to transfer during a clocking is trapped in a pixel for the duration of subsequent clockings. Some of this charge is held and released after the entire image is read-out, leaving ghost images (Biretta & Mutchler 1998). Short time-scale detrapping with an e-fold of a few clockings has been observed, resulting in a charge-deferred tail (Riess, Biretta, & Casertano 1999) in cosmic rays. Intermediate time-scale trapping is also seen in extended charge tails of hot pixels (Biretta et al. 2000). Charge trapping can help explain the dependence of charge packet loss on background as the background counts can fill-in the traps so they cannot drain the charge from sources. However, it is not possible to predict the effect of CTE on extended sources simply using the measurements of point sources.

Here we describe an exploration of the effect of CTE on the observed galaxy structure using observations and simple modeling. The effect of CTE on the photometric magnitudes of galaxies will be treated elsewhere (Baggett et al. 2000). In the following sections we describe the observations employed for this purpose, how they were analyzed, and what we can learn from them.

2. Observations and Reduction

We obtained observations of Abell 1689 (Proposal 8456) at 2 pointings and 2 filters (F814W and F606W). Each of the 4 observations had an exposure time of 2000 seconds (2x1000 sec CR splits). One pointing placed a rich portion of the cluster on WF2 and the second pointing placed the same field on WF4. This strategy resulted in 2 images of each galaxy with X and Y positions mirrored across the center of the field. In this way, galaxies which were observed at positions which were far from the read-out amplifier were also observed at positions close to the amplifier. The motivation of this observing strategy is to explore the way in which the detector position influences the apparent structure of the galaxies by digitally subtracting two images of a galaxy.

We removed cosmic rays from the pipeline-calibrated frames using the crreject routine in IRAF and the image pairs (CR splits). We employed the drizzle algorithm to correct the combined images for the known geometric distortion and differences in field size. In addition we scaled the images for the small differences in the CCD zeropoints (Biretta et al. 2000). Figure 1 shows the WF2 and WF4 frames.

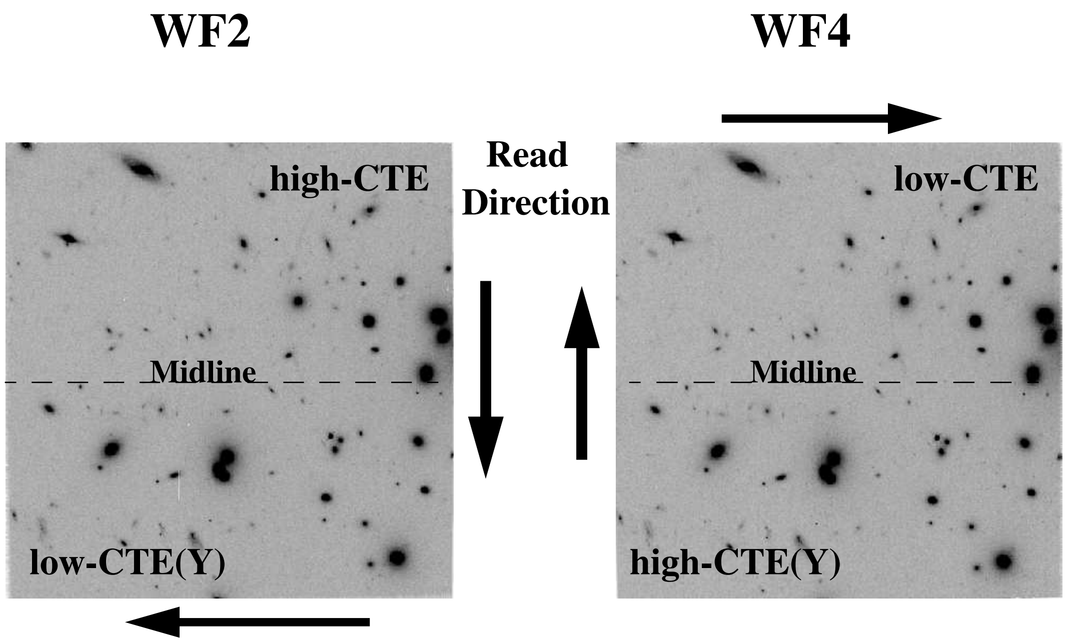

Figure 1: A field of view of 1689 observed on WF2 and WF4. Arrows indicate the direction in which the CCD frames are read-out. The dotted lines illustrate the parallel read-out midline of the frames.

3. Analysis

Our goal is to subtract geometrically aligned galaxy pairs[1] in the WF2 and WF4 frames to examine the residuals for the effects of CTE.

To align the WF4 and WF2 fields we first rotated the WF4 frames by an angle of 179.13 degrees to match the orientation of the WF2 frames. This rotation angle is the relative position angles of the WF2 and WF4 fields given in the WFPC2 handbook (Biretta et al. 2000). Next,we shifted the WF4 frames to align with the WF2 frames. This shift was derived independently by a global cross-correlation and visual inspection and experimen-

1. The galaxies selected had typical peak counts in the range of 50 to 400 DN and integrated counts of 3000 to 30000 DN.

tal shifting indicates that the accuracy of the global[2] alignment is 0.1 to 0.2 pixels in both X and Y directions.

To analyze the Y-CTE effect we plotted the galaxy residuals as a function of Y-position in the single column running through the galaxy peak. We used the following convention for subtracting pairs of galaxy images: the pixels imaged *farther* from the read-out amplifier were always subtracted from their twins imaged *nearer to* the read-out amplifier (e.g., “low Y”-”high Y”). The result is that for half of the field we subtracted WF2 from WF4 and for the other half we subtracted WF4 from WF2 (see Figure 1).

A composite residual profile was derived by averaging residuals of the ~20 galaxies nearest the Y-extremes of the chips (average position ~100 Y pixels from the edge). These are the galaxies which would suffer the largest CTE effects. In Figure 2 we show the composite galaxy residual profile along the Y-column bisecting the galaxy.

2.The advantage of *globally* aligning the images is that we are unlikely to “overalign” the images-i.e., to remove the CTE-induced asymmetries in the process of aligning the galaxies. The reason is that asymmetries induced by CTE should depend on a galaxy’s position relative to the read-amplifier. After rotation, the direction of the read-out for the WF2 and WF4 frames is opposite (see Figure 1). Any CTE effects on galaxies would therefore be opposite and equal at opposing ends of the chips, hence we tend not to remove a CTE-effect in the alignment process. The disadvantage of using a *global* alignment of the frames is that *local* shifts between galaxy pairs may persist due to uncorrected geometric distortion (despite the application of the geometric distortion map in the drizzle process). Such local shifts may be 0.1 to 0.2 X or Y pixels but should, to first order, be statistically random and hence should only add “noise” to the CTE signal. We also explore individually aligning the galaxy pairs.

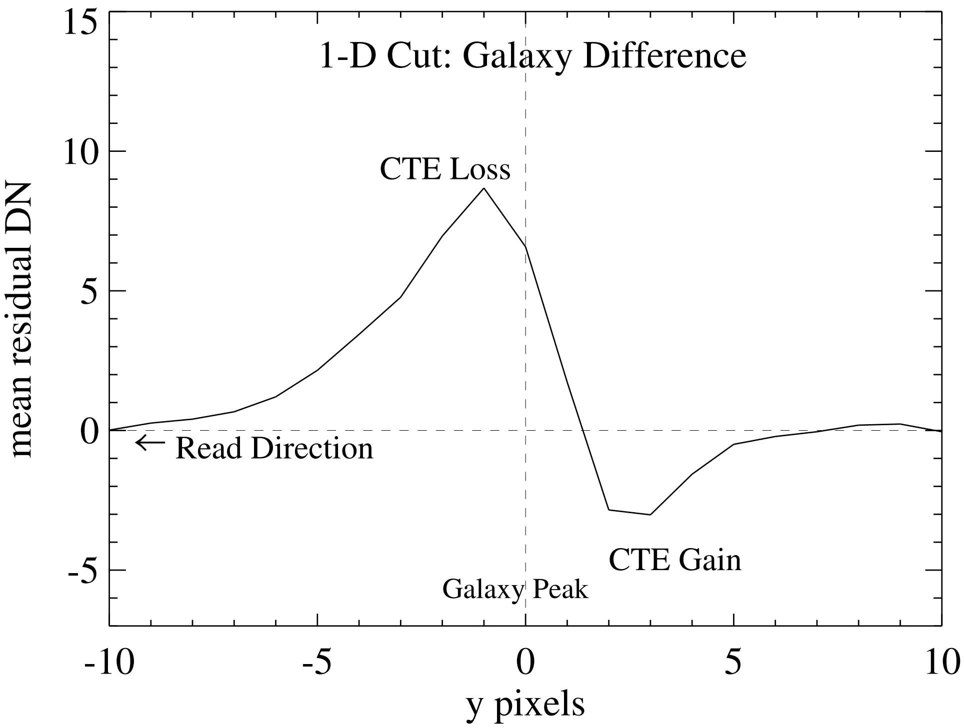

Figure 2: Composite difference profile showing the residuals from the subtraction of 20 galaxy pairs imaged near and far from the read-out amplifier. A 1-dimensional cut of this profile along the Y-axis (bisecting the galaxies) is shown.

The profile confirms the expectation; a greater amount of charge is lost from pixels which are closer to the read-out amplifier. By the time the peak of the galaxy is clocked through a pixel, most of the net losses have already occured. When the other half of the galaxy profile (i.e., the half farther from the read-out amplifier) is clocked through pixels, less charge is trapped because many of these traps are still filled by the preceding half of the galaxy's charge. In addition, CTE *gains* to the trailing half of the galaxy profile are readily apparent as negative residuals. These gains are charge deferred tails also seen to trail cosmic rays and hot pixels (Riess, Biretta, & Casertano 1999; WFPC2 Handbook). They result from charge which has been trapped and re-emitted on a timescale of a few WFPC2 parallel clockings. In Figure 3, we plotted separately the residuals originating from WF2 minus WF4 and WF4 minus WF2 to determine if these residual profiles were consistent. The galaxy residual profile is similar from subtractions at both ends of the field indicating a CTE-lie dependence on the image position.

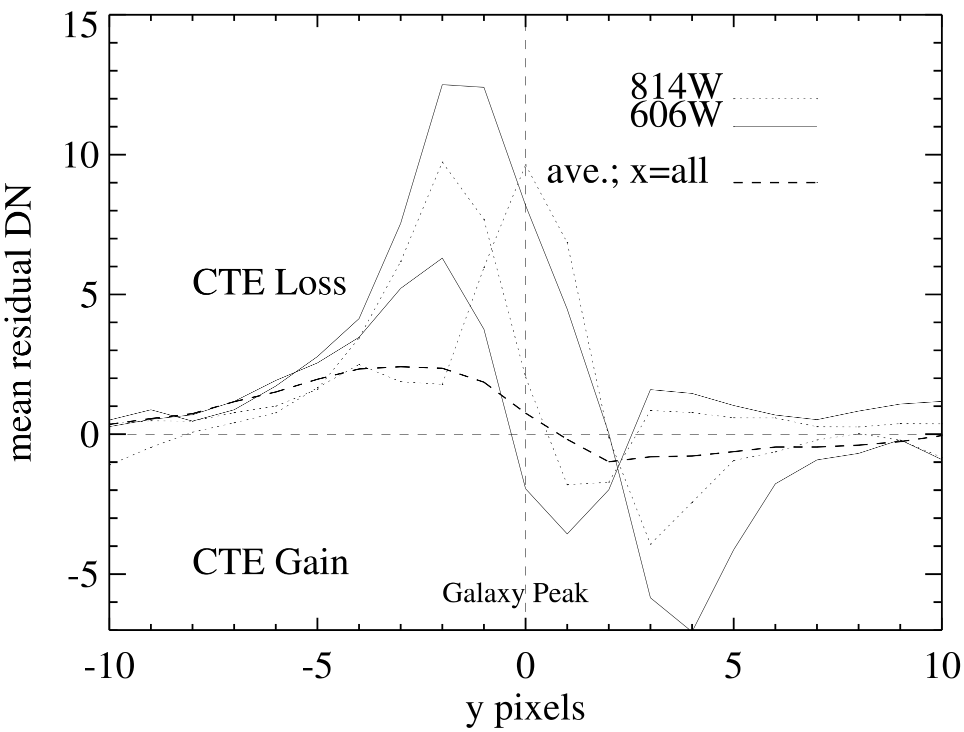

Figure 3: Galaxy residual profile versus y pixel for global image alignment. The two thin dashed/filled lines show the results from images in 814W/606W, plotted separately for WF2 minus WF4 and WF4 minus WF2 differencing. The residuals averaged over both chips are shown for a single column in Figure 1 and averaged over all columns as a thick dotted line.

The same profile of the galaxy residuals seen along the column bisecting the galaxy is also seen by "collapsing" the galaxy in the X-direction (i.e., summing the residuals along the X-direction). The main difference is that the average residual per row is less because rows off the X-midline contain less charge and thus less charge is lost.

The net loss to a measured galaxy magnitude has a small dependence on the size of the aperture used; large apertures recover some of the CTE loss by including more of the charge deferred tail. However, for typical apertures the net loss in Figure 3is ~2% of the total galaxy counts, in good agreement with the photometric losses measured by Baggett et al. (2000) and expected for point sources by Whitmore, Heyer, & Casertano (1999). *The important difference from a point source treatment of galaxy CTE is that the net photometric losses occur to the amplifier-side of the galaxy image.* The resulting asymmetry of the galaxy induced by trapping may have measurable consequences for statistical measurements of galaxy shapes, morphology, axial ratio, positional angle, asymmetry, concentration and centroid. Measurements of galaxy shear induced by gravitational lensing may profit by accounting for galaxy CTE.

Because CTE may affect the shape and symmetry of the galaxies, the method used to align the WF2 and WF4 frames may have consequences in the measurement of the CTE effect. Therefore we also aligned galaxy pairs *individually*[3] by cross-correlating galaxy

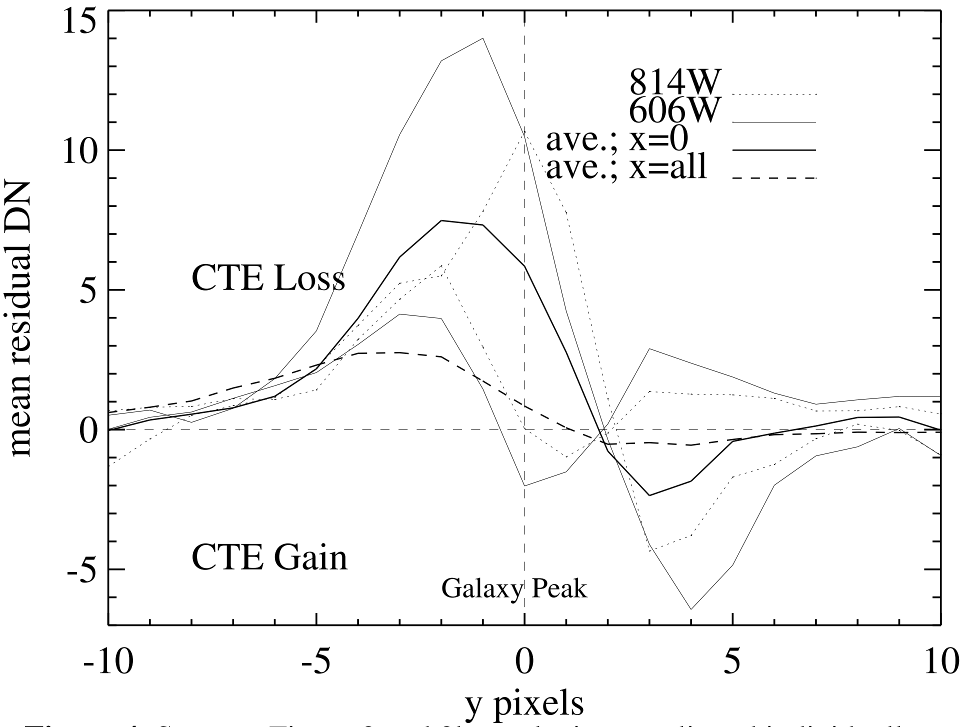

Figure 4: Same as Figure 2 and 3but galaxies are aligned individually.

"stamps". The galaxy residual profiles resulting from this approach are seen in Figure 4. Overall, the results are very similar to the results from using a single global alignment (see Figures 2 and 3). The lack of difference between the results from local and global alignment may indicate that the cross-correlations cannot improve on the accuracy of the global alignment.

Not all of the subtraction residuals will be due to CTE. Other contributors include remaining galaxy misalignment (such as a shift or a rotation) and telescope breathing. However, these contaminants can be recognized and distinguished from CTE by understanding their different symmetries in the subtraction residuals. A global shift between two images will leave a pattern of galaxy residuals which are positive followed by negative or (negative followed by positive, depending on the direction of the shift). *This residual pattern will be independent of the position on the chip.* A global rotation between the images will leave a pattern of positive and negative residuals which revolve around the

3. Specifically, we cross-correlated galaxy stamps which were 21x21 pixels centered on the galaxy peaks. The advantage of this method is that it removes local errors in the geometric distortion map. The disadvantage is that this process could somewhat overalign the galaxy pairs, i.e., remove some of the trapping-induced asymmetry in the process of aligning the stamps.

center of the rotation. Rotations around points far from the center will result in residuals which are similar to a global shift. Telescope breathing (i.e. small focus changes between frames) would create “donuts” in the subtraction residuals; a pattern with no dependence on position in the field.

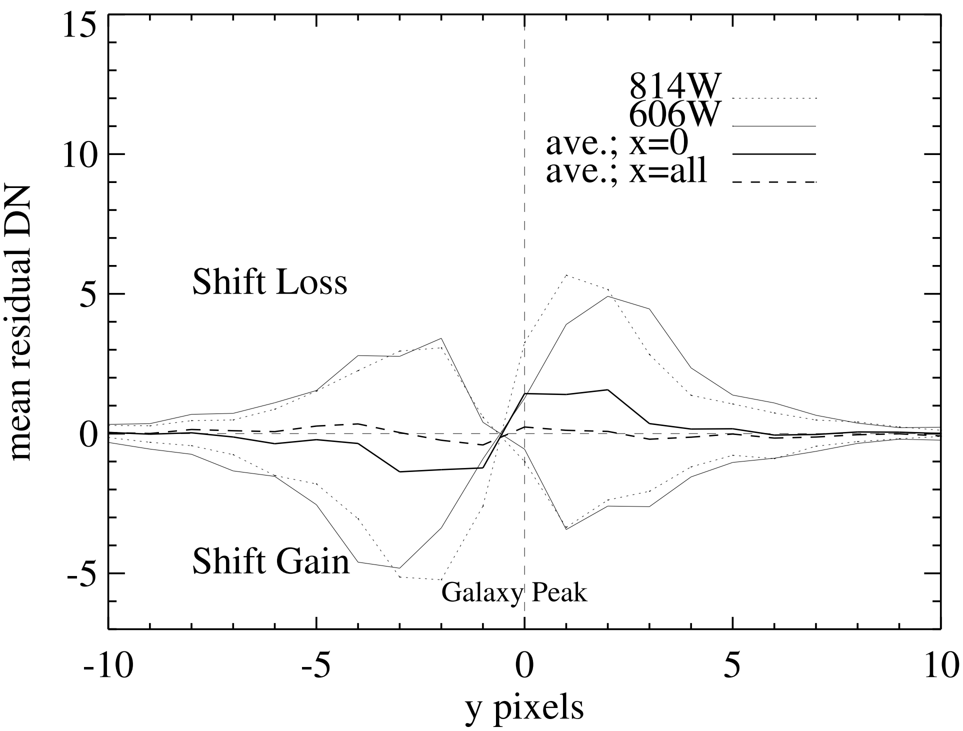

Figure 5: Same as Figures 2 and 3 but galaxy pairs are intentionally shifted in Y by 0.1 pix.

To illustrate the difference between residuals resulting from CTE and a global shift we show the galaxy residual profile from an intentional 0.1 pixel global misalignment in Figure 5. The symmetry in the subtraction residuals caused by a global misalignment is seen to be opposite of that caused by trapping. Some degree of global shift, rotation, or telescope breathing between the WF2 and WF4 frames may explain moderate differences between the peaks of the residuals seen from opposite ends of the chips in Figure 3. However, the affect of these shifts (or a rotation or telescope breathing) is effectively canceled in averaging the results from both ends of the chips.

A field size difference between the WF2 and WF4 fields (despite the geometric correction performed in the drizzle package) could leave subtraction residuals which look somewhat similar to those seen in Figures 2, 3 and 4. However, a field size difference is unlikely to be significant because the observed charge gains are much smaller than the charge losses whereas a size difference would yield equal gains and losses (and possibly of different parity than observed) In addition, the local alignment process would be expected to remove the effects of a field size difference.

4. A Simple Model of Charge Trapping

We have constructed a simple Monte Carlo model of the read-out process to better understand the results in Section 3. Our model of a CCD consists of a column of 800 pixels, each with a fixed number of traps. A “trap” is parameterized by two probabilities (or timescales); one is the likelihood that an electron clocked into the pixel is trapped and the other is the likelihood that an electron in a pixel trap is released during a clocking. Presumably many more parameters are necessary to realistically model a CCD including those for other species of traps, the number of traps per species, and a relation between the number of electrons in a pixel and the likelihood that charge is trapped. However, our simple model is sufficient to reproduce the effects seen in Section 3.

By varying the likelihood to trap and detrap we have reproduced the observed effect of trapping on galaxy profiles. The top panel of Figure 5shows the “observed” galaxy profile and its appearance after the read-out process; the bottom panel shows their difference. As demonstrated in Figures 2, 3 and 4, the net loss to the galaxy profile is greater for the half of the galaxy nearer to the read-out amplifier. Smaller losses are suffered by the other half of the galaxy because some of the pixel traps encountered have already been filled and have not had enough time to empty. In addition this region actually gains charge as electrons from the preceding pixels are trapped and released. The specific shape of the residual “S-wave” reveals a great deal about the probabilities for trapping and releasing charge. If the likelihood to trap is too low, no loss occurs; if it is very large then too much loss occurs. There is some degeneracy here between the number of traps and the likelihood to trap. If the likelihood to release charge is low, the charge deferred tail is absent, if charge release is likely then there is little net loss.

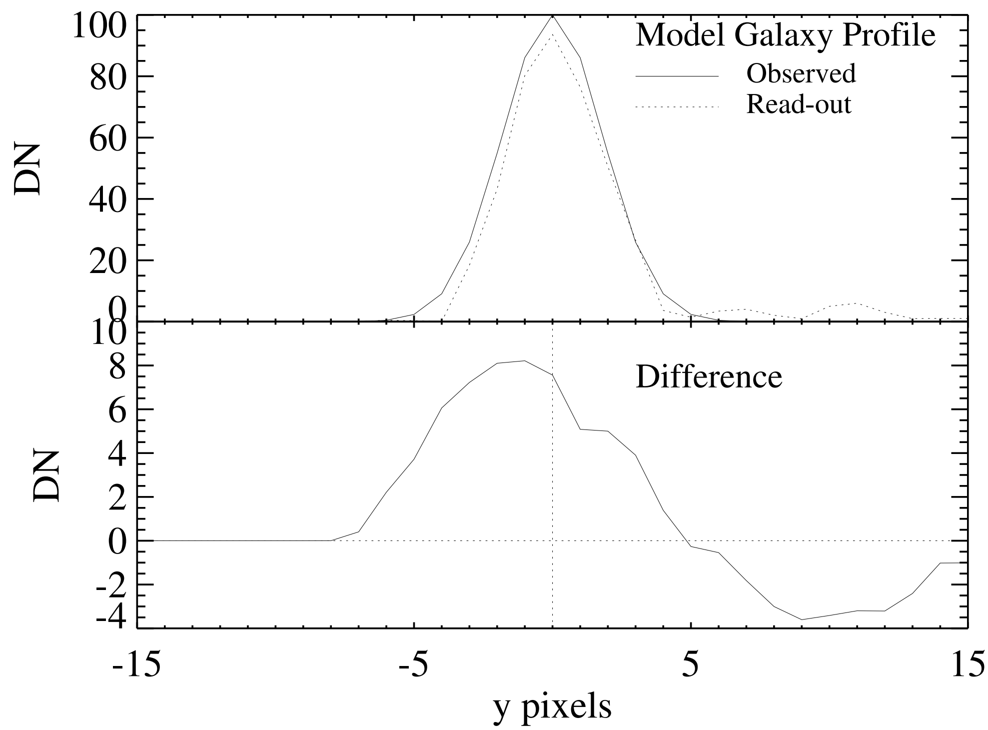

Figure 6: A model of the read-out of a galaxy image. The model gains traps which hold and release charge. The top panel shows a galaxy profile as observed and after read-out. The bottom panel shows the difference between the input and output galaxy profile.

5. Discussion

The results of the previous sections indicate that CTE losses to extended sources are not uniform across the source. Rather, they are proportionally greater closer to the read amplifier, decrease in the direction away from the amplifier, and charge is regained at the extreme edge of a source. Our knowledge of how CTE affects galaxies is still primitive and it is difficult at this point to provide a quantitative correction which can be employed by WFPC2 users. Nevertheless, we suggest that users consider that the total CTE loss expected for a galaxy (Baggett et al. 2000; Whitmore, Heyer, & Casertano 1999) likely applies only to the half of the galaxy near the amplifier, with the other half facing negligible losses. This statement appears to robustly apply to the different methods and filters (i.e., backgrounds) employed in this analysis.

We performed the same analysis to explore the effect of trapping in the X-direction (serial read-out). The galaxy residual profiles are similar in shape to those in Figures 2 and 3 but with amplitudes and total losses reduced by more than a factor of two.

By refining our model of trapping to adequately reproduce all empirical effects of CCD trapping we can ultimately learn from its predictive power. For example, we used the same model which reproduces the results in Section 3 to explore the effects of trapping on very extended sources such as planets, rings, nebulae, or nearby galaxies. Our results indicate that after an initial loss to the edge of the source nearest the read-out amplifier, the subsequent region of the image may suffer little or no net loss as charge trapping and releasing reach a near equilibrium (with the initial charge "deposit" ultimately released as a tail of charge.) A similar effect is predicted to occur in very crowded fields where sources closer to the read amplifier fill traps and release charge, reducing the net loss to sources which are farher from the amplifier. In this way, the net CTE losses to a source may depend on the "richness" of a field. Ultimately, a more sophisticated model like that described in Section 4 may be used to develop a statistical correction to the losses and smearing in complex scenes.

I would like to acknowledge valuable discussions with John Biretta, Sylvia Baggett, and Stefano Casertano which contributed to this work.

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