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Sink Pixels and CTE in the WFC3/UVIS Detector

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ABSTRACT

Post-flashed calibration products have highlighted a previously undocumented type of image defect, which we call "sink pixels" (SPs). These pixels apparently contain a number of charge traps, and as such they under-report the number of electrons that were generated in them during the exposure. We find that about 0.05% of pixels can be characterized as SPs, but they can affect up to 0.5% of the pixels when the background is low. We investigate the phenomenon here and describe future steps that will be taken to flag and perhaps correct these pixels.

1. INTRODUCTION

The realization that a low level of post-flash can considerably mitigate losses of CTE[1] (charge-transfer efficiency) has improved not only science images, but it has improved the calibration images as well. Biretta & Bourque (2013) found that when we began to post-flash the dark images, the number of warm pixels (WPs) present increased by 150% relative to the un-flashed darks (see their Figure 22). This is because in the un-flashed darks with low background, low-level WPs that were far from the readout register get trailed beyond recognition by the time they arrive at the readout register. However, in the presence of a moderate background, there are fewer open traps to impact the charge transfer efficiency, and more of these low-level WPs survive the journey to be read out. Since many science exposures have moderate backgrounds, these WPs are present in them as well, so it makes sense that we would want to include these WPs in the dark reference files so that they could be removed from the science images when we do the dark subtraction.

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[1] See http://www.stsci.edu/hst/wfc3/ins_performance/CTE/ for a discussion.

In addition to taking darks with a post-flash level of 12 e^{-}, we also must take "bias" exposures[2] with the same level of post-flash, so that the electrons that are not related to dark current can be subtracted before the dark reference file is generated. These post-flash biases show a peculiar population of low pixels that are distributed uniformly across the detector (see Fig 5 of Biretta & Bourque 2013). These low pixels are often single pixels, but they can also be arranged in vertical troughs of low pixels.

In this document, we describe the phenomenology of these "sink" pixels (SPs). We first examine them visually in darks and biases then quantify their numbers with respect to warm or hot pixels. After that, we show that they are largely delta functions when the background is high, but are broader when it is low. This behavior suggests that SPs might correspond to the sites where large numbers of CTE-loss-causing charge traps are present, so we study how the CTE properties of the row change when a pixel in that row develops a "sink", both in terms of charge lost from warm pixels and charge added to trails. All of these investigations suggest that the traps in the SPs are the same traps that cause CTE losses more generally.

2. THE SINK-PIXEL PHENOMENON

Sink pixels (SPs) can be seen in regular science images as low pixels. But in these pipeline-processed `_flt` images, it is often unclear whether the pixels are low because of errors in the pixel-to-pixel flat fields, because of dark over-subtraction, or some other issue. SPs are much easier to isolate in the unprocessed `_raw` images.

Figure 1 shows two post-flashed calibration products. On the left is a stack of fifteen 800s darks with 100 electrons of post-flash (from CAL-13567, PI Anderson). There are many WPs visible in this exposure. They show up as dark points in this negative gray-scale image, often with upward-stretching CTE trails. But there are also some white low pixels that dot the detector. On the right, we show a similar stack of 94 "bias" images, each taken with 12 e^{-} of post-flash. The white sink pixels show up much more clearly here, and they are also much more extended in the vertical direction than in the panel on the left.

From the fact that the pixels appear to be point-like when the background is higher, it is tempting to hypothesize that they may be pixels that have a greater-than-nominal number of charge traps inside them. When the background is 100 e^{-}, then all the traps are filled, but when the background is lower it may take several upstream pixels of 12 e^{-} each to fill all the traps that are present in the low pixel. We investigate this in §4 below.

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[2] We note that because of commanding restrictions, it is not possible to take true bias images with post-flash, but we can take 0.5s dark exposures. Since even regular bias images have about 3s delay from the start of the exposure to the start of readout, these exposures will effectively have 3.5s dark-time instead of 3s. This is not a significant difference.

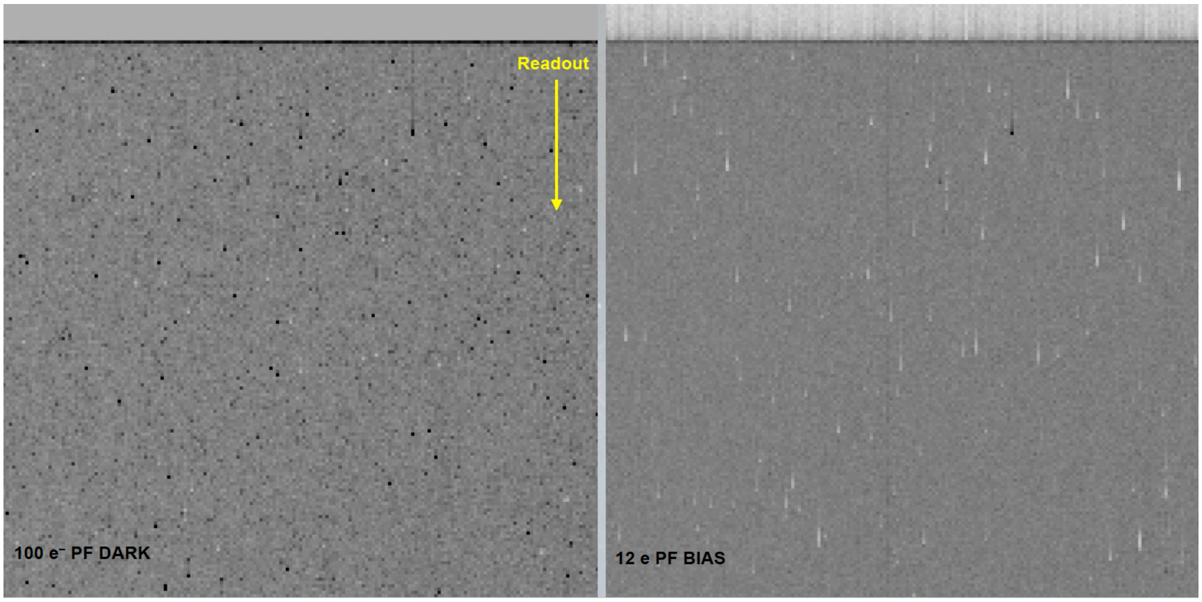

Figure 1: A 200×200-pixel region at the top of the C amplifier. Black here corresponds to higher pixel values, and white lower pixel values. (Left) 800s dark with 100 electrons of post-flash. (Right) "Bias" image taken with 12 electrons of post-flash. The top 19 rows correspond to the vertical overscan pixels. The white pixels are the SPs. On the right, the CTE trails in the overscan are readily seen; on the left, they are present, but below the lowest grayscale level. The two rows of high pixels at the top of the science pixels correspond to rows 2050 and 2051, which appear to be taller (and thus collect more of the post-flashed photons) than the other rows.

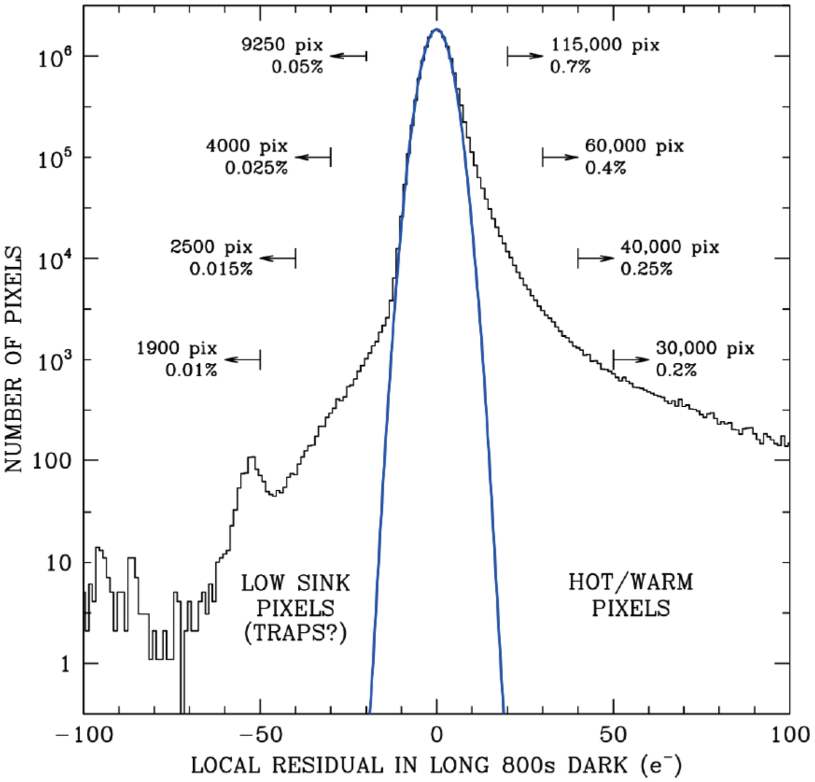

Figure 2: Distribution of pixel values with respect to a local average in the stack of 800s darks with $100e^{-}$ post-flash.

3. THE STATISTICS OF SINK PIXELS

Figure 2 shows the distribution of pixels in the 15-exposure 800s dark stack with 100 e^- post-flash. Most of the pixels are distributed about the background with a Poisson error of ~ 2.5 e^- (10 $e^-/\sqrt{15}$). This is a typical exposure time for a science image, so the number of warm and hot pixels is about what one would see in a many science exposures. About 1% of the pixels have more than 20 electrons from dark current. On the negative side, we see that about 0.05% of the pixels are low by more than 20 e^-. These are the "sink" pixels (SPs); and there are SPs that are up to 100 e^- low[3].

Five pixels out of 10,000 do not seem to imply a very serious problem, but this issue is compounded when the background is lower. The 12 e^- post-flash bias in the right panel of **Figure 1** shows that single sink pixels in the medium-background image can translate to long streaks in the low-background image.

For instance, a pixel that traps 50 e^- in a high-background image will trap (say) 10 e^- in each of the five adjacent upstream pixels in a low-background image. In practice, we find that about 0.5% of the pixels in images with 12 e^- background are impacted by this at the 7-e^- level (which is 2 sigma of the readnoise). Furthermore, these errors are correlated up the columns, such that a particular star or galaxy on a low-background image will be significantly affected.

4. SINK-PIXEL PROFILES

Figure 1 showed that the profile of a given SP often changes with the background level. In high-background images, SPs often impact only one pixel, but in low-background images they can turn into vertical streaks. Program CAL-13567 takes a range of short dark exposures with backgrounds from 0 to 120 electrons; it provides an easy way to examine SP profiles as a function of background.

We identified a set of SPs that were 35±5 e^- low in the 100-e^- post-flashed darks. We examined that set of pixels and the pixels above and below them in images with a variety of backgrounds, from near zero electrons to about 85 e^-. The left panel in **Figure 3** shows the SP profiles at the bottom of the chip, close to the readout register where CTE losses are small. The panel on the right shows the profiles for the top of the chip, where CTE effects are largest. (The charge-transfer-inefficiency blurring experienced by the SP profile as it is transferred down the detector naturally comes from different traps from the traps in the SP itself.)

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[3] It is, of course, not possible to be more than 100 e^- low in this data set (which has darks with 100 e^- of post-flash), since a sink cannot trap more electrons than were initially present in the pixel.

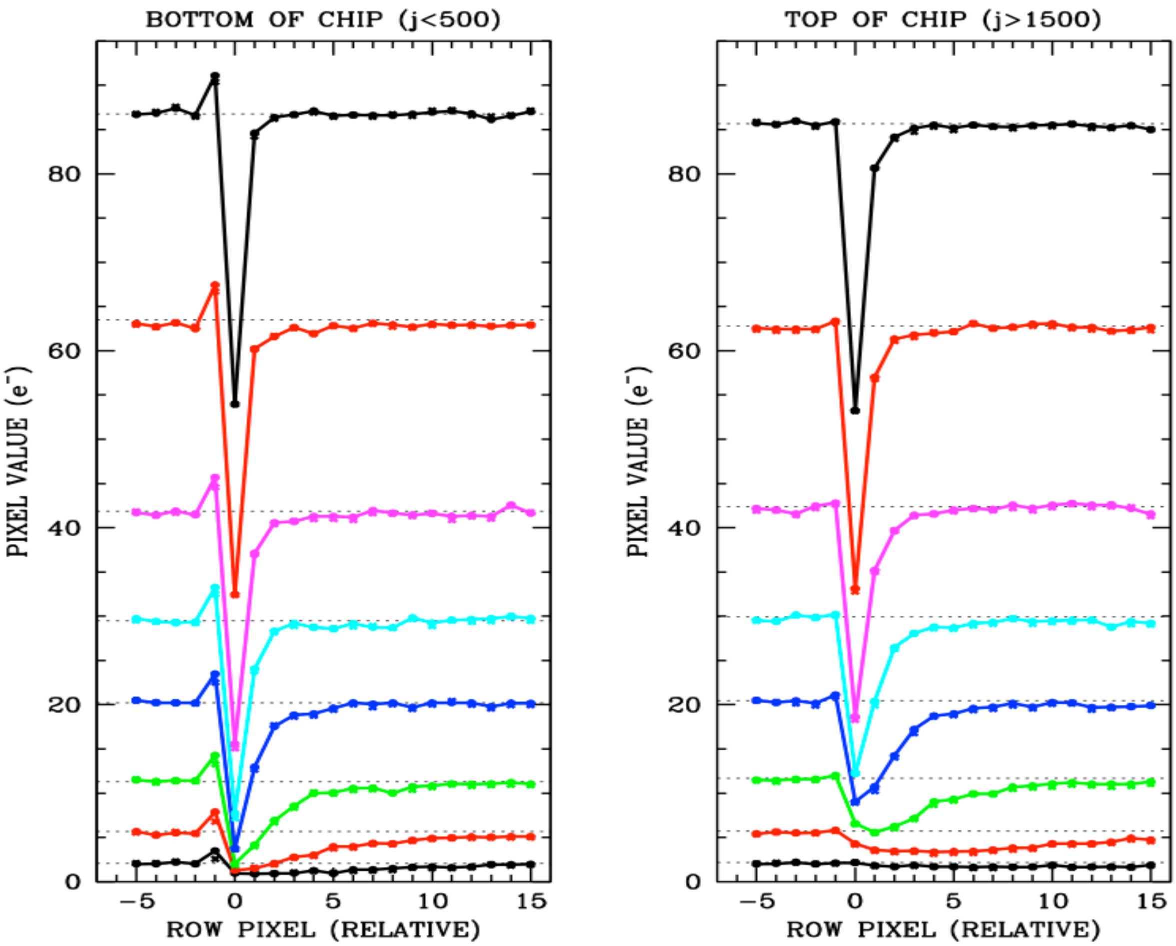

Figure 3: The average vertical profiles for sink pixels that contain about 35 traps in them. The different colors correspond to images with background levels of 2, 5, 10, 20, 30, 40, 65, and 85 electrons. The panel on the left shows the average profiles for many similar SPs close to the readout register. These profiles should suffer minimally from CTE blurring. The panel on the right shows average profiles for SPs near the top of the detector, far from the readout register. These profiles should be maximally blurred by charge-transfer errors.

In both panels, the SP largely creates a delta-function dip when the background is high (the black curves on the top). The pixel above the SP (at +1 on the x-axis here) is generally between 2 and 5 electrons lower than the background. It is ambiguous how much of this is related to the SP grabbing some electrons when the next pixel goes through it and how much is related to CTE modifying the shape of the delta-function SP as it is transferred down the detector. Some of the flux decrease in the +1 pixel is clearly due to CTE issues, since the trough is broader in the right panel than in the left panel.

As the background goes down, the profile becomes broader and broader. Close to the amplifier, the SP itself is always the lowest pixel, but far from the amplifier it turns out that sometimes the minimum of the trough is found in the pixel *above* the SP (at +1 on the horizontal axis). This makes sense in that the trough must start its journey looking something like what we see on the left, then as the pixels are shuffled down the detector, the first pixel acquires some electrons, due to the release of previously filled traps. The pixel upstream of the SP (at +1) experiences less of this filling (since CTE trails have about twice as many electrons come out after one transfer than after two); so sometimes it turns out that the pixel *above* the SP ends up being read out as lower than the SP itself.

It is worth noting that these troughs appear to have roughly the same number of electrons in them. When the background is high, the trap's impact is essentially a delta function. When the background is low, it often takes several pixels worth of electrons to fill up the traps in the SP. It is of course not clear whether there are multiple traps in each pixel (each trap holding one electron), or whether the affected pixels have just one multi-electron trap. From an empirical standpoint, this seems to just be a matter of semantics, but either way it is clear that there are some pixels on the detector that can trap many more electrons than the typical pixel.

Finally, we note a curiosity that was also noted in Biretta & Bourque (2013). Sometimes the pixel *downstream* of the sink pixel (at "−1" on the horizontal axis in **Figure 3**) is on average *high* relative to the background. This is not true for every sink pixel, but it appears to happen about 30% of the time near the bottom of the detector and 20% of the time near the top of the detector. The effect is much larger in amplitude closer to the readout register (left panel) than farther from it (right panel). It is not at all clear what this represents. One idea is that it may be due to the mechanics of the readout itself. When the readout begins, the electrodes squeeze the charge collected in each pixel into a third of the pixel so that it can be coherently shuffled down the detector. If there are any filled traps in the regions of the silicon that are beyond the regions into which the charge is squeezed, and if these traps release electrons in the 3 seconds before the vertical charge-shuffle starts, then some of the released electrons may end up not in the original SP, but some may end up in the pixel above or below the SP. If these electrons end up in the pixel above the trap, then they will likely be grabbed by the trap again. But if they end up in the pixel below the SP, then they have a good chance of making it to the register. We have a newly approved supplemental-calibration program (CAL-13638) that should allow a more thorough study of this phenomenon.

5. HOW DO INDIVIDUAL SPS BEHAVE OVER TIME?

Phenomenologically, it makes sense that sink pixels likely represent enhanced cases of the same the same charge traps that cause the CTE blurring that so plagues radiation-damaged detectors. It should be possible to test this hypothesis. To do this, we identified a sink pixel close to the top of one of the detectors. We chose the SP at $i_{RAW} = 209$ and $j_{RAW} = 2036$, which registers about 50 e^- low when the background is 100 e^-. (The RAW coordinate designation refers to the fact that this coordinate is given in the raw image frames, which have the science pixels starting at column $i_{RAW} = 26$.)

For various purposes, we have collected together all of the WFC3/UVIS full-frame images into a single database that makes it easy to explore the behavior of individual pixels over time. More than 30,000 WFC3/UVIS full-frame exposures have been taken since WFC3/UVIS was installed in May 2009, and we have generated "master" images that contain the time-history of each of the 8412 columns in the camera (2103 columns for each of the four amplifiers). There is one "master" image for each column, and each image is 2070 rows tall and 36,000 pixels wide. These master images allow us to follow the time evolution of every pixel in that column as it observes the sky, dark, bias, or flat in various exposure times, filters, setups, etc.

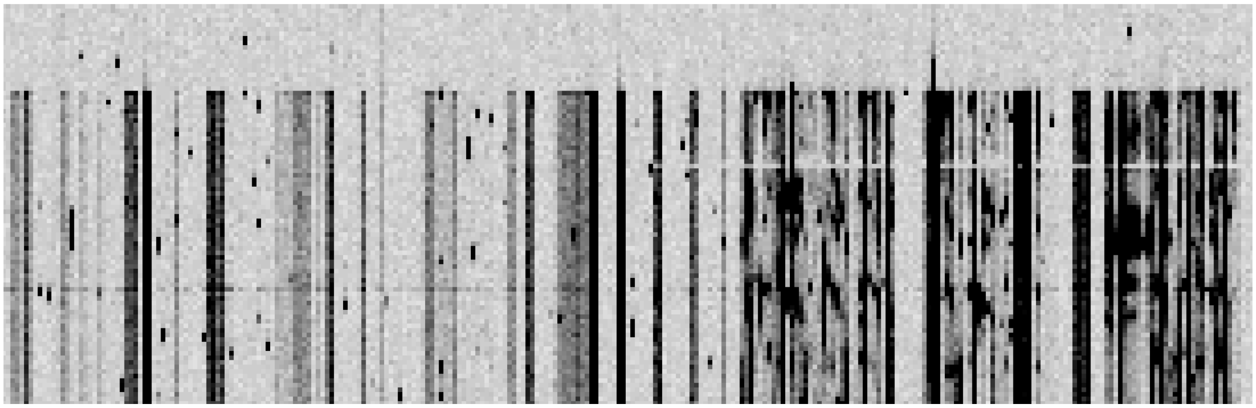

Figure 4: This is a small portion of a "master" image, which records the time history (along x) of every pixel in a particular column of the detector. This image shows exposures 3620 through 3895 for rows 1970 through 2070.

Figure 4 shows the top portion (i.e., far from the readout register) of the "master" image for column $i_{RAW} = 209$. Each column in this image represents a single exposure, and as such has a different background, depending on the exposure time, target, and instrument setup. Each row represents a different pixel up this particular column ($i_{RAW} = 209$). The horizontal portion shown represents exposures 3621 through 3895, taken between 31 December 2009 and the 15 January 2010. We show the top 100 pixels of the column. The top 19 pixels correspond to the vertical overscan; these are not always empty because CRs can hit the virtual pixel during readout and because of the CTE trails that come from traps filled by the science pixels. As in **Figure 1**, this image is scaled such that white represents low values and black high values.

About two-thirds of the way down the image, there is a pixel that is often higher (darker) than its neighbors much of the time. This is a warm pixel. It isn't always higher than its neighbors because sometimes the exposure time is short.

About 15 pixels down from the overscan boundary there is a pixel that looks normal for about half the pixels shown, but then all of a sudden it becomes a sink pixel, appearing white. In image number 3765 (ib4405jhq taken on 10 jan 2010 at 5:20am) the pixel seems to change from being "normal" to being lower than its neighbors. Coincidentally or not, there was a cosmic ray event at this pixel location in the previous image (taken three hours earlier). It seems more likely that the damage occurred while an exposure was not in progress, though we could certainly collect some statistics on this from the Master images.

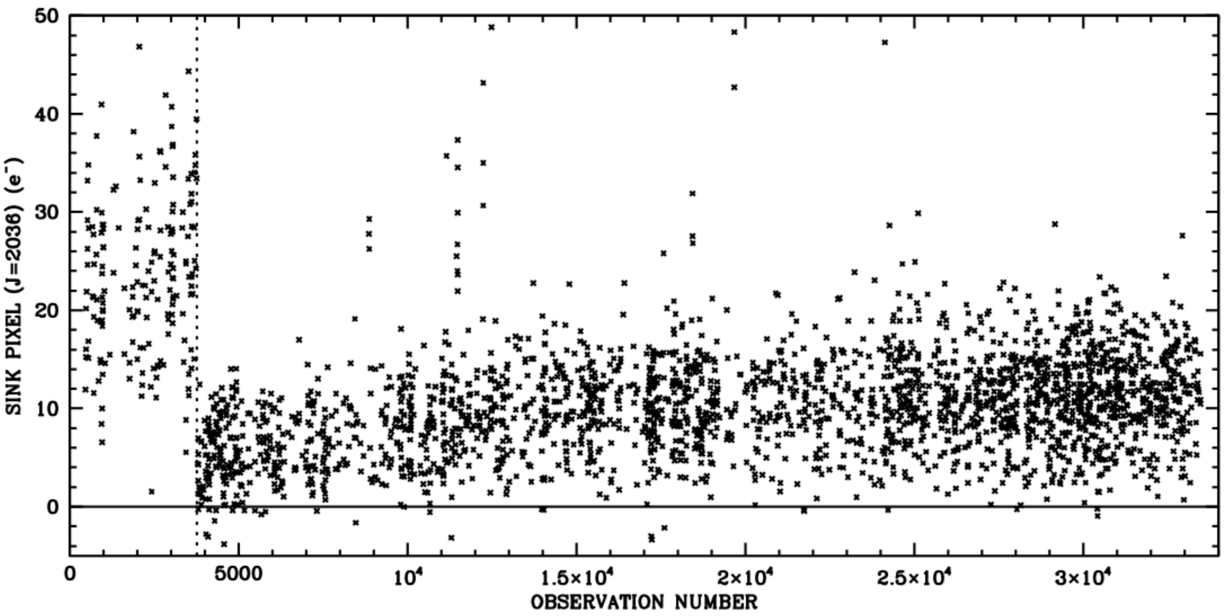

Figure 5: The entire time history of sink pixel iraw=209, jraw=2036 (for images with backgrounds of about 25 electrons).

Figure 5 shows the entire time history for this sink pixel. The pixel experiences a drastic event early in its life, but after that it appears to be quite stable (though always low). The gentle upward trajectory from the SP creation to the present is indicative of the secular increase of CTE blurring over four years resulting in CTE trails from the downstream pixels partially filling in the SP.

All of the SPs we have examined in detail so far appear to have been generated over time on orbit, but we have not done a comprehensive study of all of them, and there may well be some that were present at launch. We will explore this in a future ISR. The new calibration proposal should allow us to document all current sink pixels, and we can determine from the "master" images when each of them turned on, whether they are stable, etc.

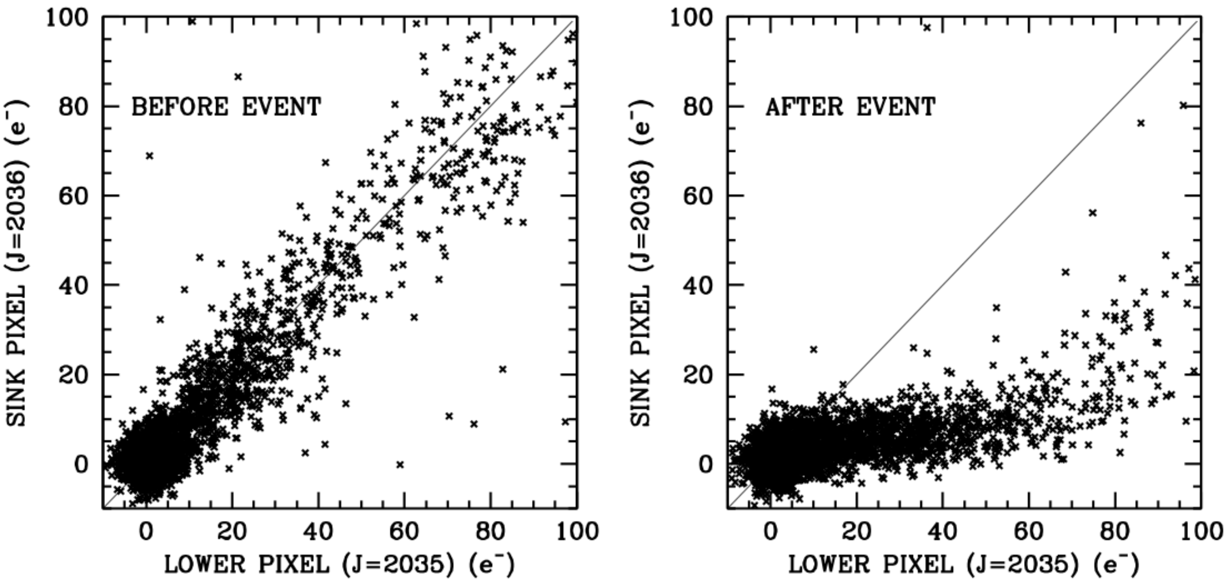

Figure 6: These panels show the value of the sink pixel as a function of the value of the pixel below it (which is a proxy for the local sky, and the number of electrons the pixel *should* have contained). On the left, we show the correlation for the 1000 exposures before the event, and on the right for the 1000 exposures after the event.

Figure 6 above shows the same SP in the ~1000 observations before the event and the 1000 observations after the event. We plot the value of the sink pixel against the value of the pixel below it, which is a proxy for the background (i.e., the expected value in the SP itself). In the left plot, we see a clear 1:1 correlation between the background value on the *x*-axis and the value in the sink pixel on the *y*-axis. In the right plot, this changes dramatically. When the local background pixels contain 40 electrons, the SP contains only 5. When it should contain 100, it contains only 50. This is all consistent with this pixel containing about 50 traps.

It is clear from **Figure 6** that there is a non-linear relationship between the registered value of the sink pixel and the number of electrons that were initially deposited in it. For high backgrounds, there appears to be a 1:1 linear relationship, with the sink pixel simply being about 50 electrons low. For backgrounds below 50 electrons, the sink clearly cannot absorb more electrons than are put into it, so it just absorbs most of the electrons it starts with. There is a transition region between a background of zero (where the pixel appears normal) and a background (here around 50 electrons) where the sink just removes a constant number. This could clearly be fit with a simple two-parameter model.

6. DO SPS CAUSE TRAILS LIKE CTE CHARGE-TRAPS?

In order to test whether the SP charge traps are related to the charge traps that lead to the losses and trailing of imperfect CTE, we decided to explore the vertical overscan pixels above the particular sink event discussed in the previous section. The vertical overscan pixels are "virtual" pixels. When the detectors are read out, the top row is shuffled into the row below it. This leaves the top row empty. This empty row is then shuffled down the detector like a real row. When the detector has read out the top physical row of the detector (j=2051), it continues to read out 19 more rows. Although each of these 19 virtual-overscan rows started out completely empty at the top of the detector, by the time the row arrives at the readout register, it may have picked up some electrons. These pixels can contain dark current from the charge emitted from hot pixels while they are temporarily occupying them during the downward shuffle. They can also contain some CTE-trail electrons. When real pixels with real electrons are shuffled down the detector, charge traps can sometimes grab electrons, hold them for a while, then eventually release them into upstream pixels. These overscan pixels can be the recipients of released charge.

To examine whether the creation of these sink pixels corresponds to the introduction of additional charge traps in the column, we can simply look at the corresponding overscan pixels. **Figure 7** below shows the flux in the sink pixel and the corresponding overscan as a function of time. As in **Figure 5**, we have selected those exposures that have a background of about 25 electrons and examine the time history of the sink pixel (bottom panel) and the first overscan pixel (top panel) in the observations just before and just after the event.

The bottom panel shows the drastic change that takes place in the sink pixel on 10 January 2010. It transitions from reflecting the background at 25 electrons to containing about 5 electrons, as we saw in **Figure 6**. At the same time, the overscan transitions from having an average of about 2 electrons to having an average of about 8 electrons. This sink pixel ends up contributing about 6 extra electrons into the first pixel of the overscan. The first pixel in a CTE trail contains about 25% of the total trail flux, so this increase of six electrons corresponds to a total number of about 25 new traps (or one new trap that grabs 25 electrons).

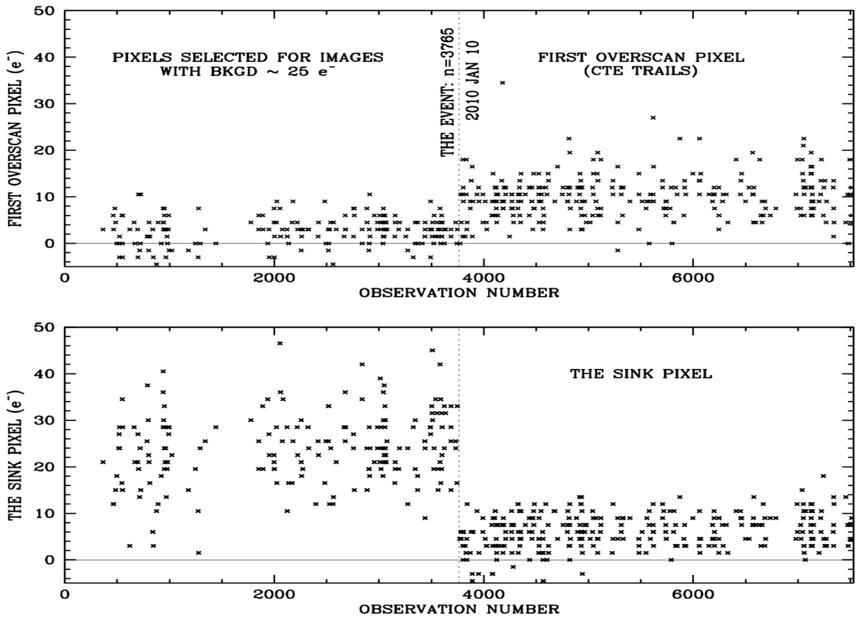

Figure 6: The time evolution of the sink pixel (in the bottom panel) and the corresponding overscan pixels (in the top panel).

7. DO SPS TRAP CHARGE FROM UPSTREAM PIXELS?

The previous sections have demonstrated that SPs end up trapping charge from electrons that land in that pixel and also end up generating trails, very similar to CTE-related trapping. It seems likely that the SPs also correspond to the locations where charge-transfer inneficiency takes place. In order to complete this connection, we have identifed a column where a SP appears below a relatively steady warm pixel. (It was surprisingly challenging to find such a pair; there aren't an enormous number of SPs, and WPs are rarely stable from anneal to anneal.)

The image on the left in **Figure 8** shows a sink pixel at [736,16] in the C Amplifier and a warm pixel at [736,154]. The upper plot shows that WP starts out being unstable, but it settles down for most of 2010 and 2011. It appears to be "healed" in mid 2013. At approximately the same time that the SP develops in 2012, we see this upstream WP losing about 10 electrons of its previously stable 70-electron dark current. This is confirmation that the addition of the SP has a direct effect on the charge-transfer efficiency in the upstream pixels.

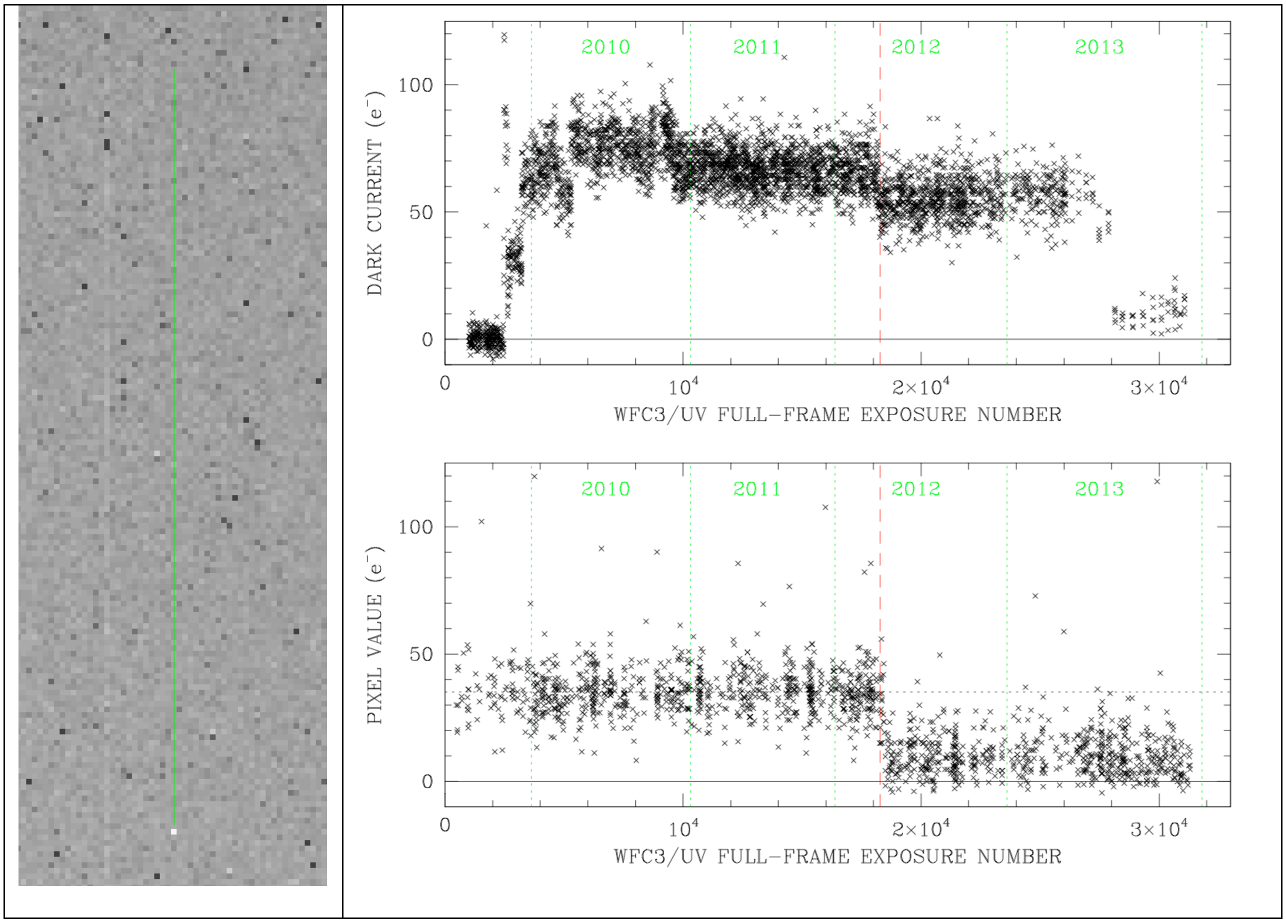

Figure 7: (Left) Image of a portion of the 800s 100e post-flashed dark, near the bottom of the detector (close to the readout amplifier). Here again, white corresponds to low pixel values and black high pixel values. The green line connects the SP and the WP. (Lower right) The time history of this particular sink pixel, which develops traps in 2012. (Upper right) The dark current in the upper WP as a function of time in dark exposures with no background.

We examined in more detail the timing between the formation of the sink pixel and onset of the increased losses in the WP and found that the losses in the top panel set in in the middle of an anneal period, but the SP does not develop until immediately after the next anneal. This might tell us something about how SPs develop and could merit further study.

8. NEXT STEPS

The above analysis shows that SPs represent an increasingly important artifact in WFC3/UVIS images. It is now clear that (1) sink pixels correspond to locations on the detector where radiation damage has created traps in the silicon lattice, and (2) these traps also lead to CTE losses and trails when pixels are transferred through them.

In principle, a calibration program might be able to map out the locations of *all* of the sink pixels, and (presumably) all the charge traps that cause CTE. But that would be difficult, since the number of traps accessible to a pixel depends somewhat on how many electrons that pixel contains. Such a calibration would require post-flashed biases at a great many different post-flash levels. Furthermore, such a program would require many exposures at each level of post-flash, since it would be necessary to beat down the readnoise and Poisson noise to measure the *exact* number of electrons that get trapped at each level in every pixel.

Nevertheless, even though an exact accounting of the locations and levels of charge traps may be impractical, the sink pixels do tell us something interesting. They show that charge traps do not appear to be distributed randomly across the detector. At least some of the traps are quite significantly clumped, often with 40 or more traps in a given pixel. **Figure 7** heuristically suggests that clumped traps may constitute a reasonable fraction of the total number of traps present, since the advent of the one SP increased the CTE trail in the overscan by a factor of four.

Finally, although the SP phenomenon is related to CTE losses, we note that the pixel-based CTE correction is unable to correct for SPs, since the current model assumes that the charge traps are located uniformly across the detector. If we hope to correct for SPs, we must use an additional calibration strategy. To this end, CAL-13638 (PI-Anderson) will be taken at the end of June 2014 and will take "bias" images with post-flash backgrounds of 25 e^-, 50 e^-, and 100 e^-, to supplement the 12-e^- post-flash "biases" that are taken as a part of the dark-reference-file program. These "biases" will allow us to catalog all the SPs in the detector (at least at the epoch of the calibration program), so that at the very least these pixels and the pixels they impact can be flagged in the DQ arrays. Additionally, it might be possible to determine a profile for each individual SP at the four fiducial background levels, so that an interpolated profile can be constructed for images with arbitrary backgrounds from 0 to 100 e^-. One could imagine adding this empirical trough back into the science images, but it is unclear how real astrophysical sources might affect the shape of the trough, and it will probably be safest to just flag the pixels that are not reliable. Stay tuned.

References

Biretta, J. & Bourque, M. "WFC3 Cycle 19 & 20 Dark Calibration Plan: Part 1" WFC3/ISR 2013-12