A characterization of persistence at short times in the WFC3/IR detector

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ABSTRACT
Persistence in the WFC3/IR detector appears to decay as a power law as a function of time elapsed since the end of a stimulus. In this report we study departures from the power law at times shorter than a few hundreds seconds after the stimulus. In order to have better short-time cadence, we use the Multiaccum (.ima) files, which trace the accumulated charge in the pixels as function of time, rather than the final pipeline products (.flt files), which instead report the electron rate estimated via a linear fit to the accumulated charge vs. time relation. We note that at short times after the stimulus, the absolute change in persistence is the strongest, thus a linear fit to the accumulated signal (the .flt values) can be a poor representation of the strongly varying persistence signal. The already observed power-law decay of the persistence signal, still holds at shorter times, with typical values of the power law index, $\gamma \in [-0.8, -1]$ for stimuli that saturate the WFC3 pixels. To a good degree of approximation, a single power law is a good fit to the persistence signal decay from 100 to 5000 seconds. We also detect a tapering-off in the power-law decay at increasingly shorter times. This change in behavior is of the order of $\Delta \gamma \sim 0.02 - 0.05$ when comparing power-law fits performed to the persistence signal from 0 up to 250 seconds and from 0 up to 4000 seconds after the stimulus, indicating that persistence decays slightly more rapidly as time progresses. Our results may suggest that for even shorter times, not probed by our study, the WFC3 persistence signal might deviate from a single power-law model.
1 Introduction

The near infrared detector of the Wide Field Camera 3 (WFC3/IR) on board the Hubble Space Telescope (HST), like other HgCdTe IR detectors, suffers from persistence: when pixels are exposed to large incident light levels, a residual signal can be detected from minutes to hours or even days afterwards. According to the model by Smith et al. (2008), persistence in such detectors can be explained as a trap-and-release of charge by detector defects in the diode depletion region. Charge is captured during the exposure, when the depletion region shrinks and traps are exposed to the photo-generated charge before it is read out. The trapped charge is then released at later times. A variety of calibration programs have been carried out to characterize persistence in WFC3/IR (Long et al. (2010, 2012, 2013b,a, 2014, 2015a,b, 2016); Long & Baggett (2018)). Typically, the detector is exposed to a known stimulus and the decay of persistence is recorded in a series of subsequent dark exposures.

The expectations from a simple physical model of the trapping mechanism, like a finite potential well in quantum mechanics, would be for the persistence signal to decay exponentially with time. On the other hand, this simplistic approach fails in describing the observation in the case of the WFC3/IR detector. In fact, as reported by McCullough & Deustua (2008), the time evolution of persistence in the WFC3/IR array is slower than what would be expected for an exponential decay, and can be characterized as a power law (A-gamma model) of the form:

\[ p(t) = A \times t^\gamma \]  (1)

where:

- typical persistence values are 0.3 e^- s^-1 at t = 1000s since the ned of the stimulus, for a stimulus of 10^5 e^- (i.e. 1.25 times the typical WFC3/IR pixel full-well capacity of \( \sim 80000e^- \)), for reference the typical dark current in WFC3/IR is \( \sim 0.04 e^- s^-1 \);

- the value of \( \gamma \) is about -1;

- the slope, \( \gamma \), and the normalization, \( A \), depend on both the total stimulus fluence (integrated number of incident photons) and the exposure length, thus reflecting the fact that stimuli of shorter duration, at fixed total stimulus fluence, produce less persistence. This can be interpreted within the Smith model as due to the finite trapping time and to the fact that for longer exposures, traps are being exposed to free charge for longer times and are thus more likely to capture free electrons.

2 Motivation

Past analysis by the WFC3 team has focused on calibrating persistence using data taken several hundreds to thousands of seconds after the stimuli. It is however clear that the A-gamma model cannot be extrapolated, with negative \( \gamma \), down to \( t \to 0 \) as it would diverge and become unphysical. The analysis in the current work is aimed at understanding persistence in WFC3/IR at times as short as 100s after the end of the stimulus. This is useful for improving characterization of persistence that happens within a single HST orbit. Short-term persistence is also related to the ramp-up, or conditioning phenomenon during
observations of transiting exoplanets. In multi-orbit visits aimed at detecting a transit, the measured flux at the beginning of each orbit is slightly lower than at the central or the end point of the orbit, thus limiting the accuracy with which the off-transit flux can be recovered. Within the Smith et al. (2008) model, this effect can be related to traps filling and effectively decreasing the number of detected photons. Such an effect would be stronger in the first orbit than in the subsequent ones, since in later orbits some traps stay filled and fewer new photo-electrons are trapped (see e.g. Long et al. (2014); Zhou et al. (2017)).

3 The data

The typical WFC3/IR calibration program for persistence studies consists of a series of stimuli (either bright astronomical targets or flat-like illumination using the internal lamps), followed by dark exposures. In such a setup, persistence is measured in the darks as a function of the fluence and exposure time in the stimulus image. Calibration Program 14016 (PI: K. Long) was however designed to allow measuring persistence in on-sky exposures as well. The idea was to observe a star cluster and then perform dithers of several tens of pixels, large enough to move the pixels away from their original stimulus source. The same target is then re-imaged. Thus no instrument reconfiguration is required between exposures, and with compact enough dithers, the small angle maneuvers are very fast, therefore persistence can be in principle measured 40-50 seconds after the stimulus.

Program 14016 used dithered observations of the bright young cluster Westerlund 1 (RA, Dec) = (16h 47m 04s, −45° 51′ 0″). Young star clusters provide a broad dynamic range of stimuli, with some stars reaching total fluences of several hundreds of full-wells (FWs) of the WFC3 detector (FW is on average about 80000 e−). The dithered observations of Westerlund 1 are followed by a set of darks. There are 3 visits in this program, with a different number of dithers on the cluster, all followed by the same number of darks (the first dark is of different duration with respect to the 15 following, identical ones). The combinations of exposure times and up-the-ramp sampling sequences are listed in Table 1. In the following we will interchangeably refer to cluster exposures, external exposures or externals. Each visit consists of two orbits, with the external exposures filling up the Westerlund 1 visibility window in Orbit 1, and the darks filling up the occultation time of Orbit 1 as well as the full duration of Orbit 2 (see Figure 1).

For reasons we will highlight in section 3.1, we could not use the external exposures to measure persistence. Thus we lost some of the advantages that should have been in principle provided by the design of Program 14016. We measured persistence only in the darks, thus our shortest time after stimulus probed is about 80 seconds.

Each cluster exposure within a visit can be considered as stimulus for the subsequent exposures and as persistence image for the previous ones; dark exposures are never used as stimuli but are valid exposures for measuring persistence. While exposures within a single visit (both clusters and darks) are consecutive, the 3 visits are not executed in a consecutive sequence, thus the first visit cannot be used as stimulus for the second and so on. Figure 2 shows a subset of images for our program, specifically the 3 cluster exposures and the first 4 darks for visit 3.
Table 1: The exposure sequence for HST Calibration Program 14016. While number of dithers, single exposure duration and up-the-ramp read sequences differ for the Westerlund 1 exposures, the dark exposures sequences following the externals are the same for all 3 visits. Sampling sequence names are defined in Section 7 of the WFC3 Instrument Handbook (Dressel & the WFC3 team (2017))

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<th>Exp. Time [s]</th>
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<th>Samples</th>
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<td>SPARS25</td>
<td>15</td>
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First Dark Sequence

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Second Dark Sequence

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<th>Exp. Time [s]</th>
<th>Sampling sequence</th>
<th>Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, 2, 3</td>
<td>15</td>
<td>352</td>
<td>SPARS25</td>
<td>15</td>
</tr>
</tbody>
</table>

3.1 The challenge of analyzing the external exposures

The external exposures of Westerlund 1 do in principle allow measurement of very short term persistence. Only $\sim 42$ seconds elapse between the end of an external exposure and the beginning of the next one. The experimental setup of HST Calibration Program 14016 was indeed intended to allow this type of measurement. The calibration program being discussed here is more complex than the typical persistence calibration, i.e. one stimulus followed by darks, and that this is because we wanted to measure the effects of persistence in a field that is rich with stars, and where the various exposures are dithered. The code developed in the current work to trace the exposure history of individual pixels was especially designed to allow identification of pixels in the external exposures suitable for measuring persistence (see Section 4).

The choice of target, Westerlund 1, was a trade-off between the number of stars and the amount of available background pixels. During the analysis it became clear however that the measurements of persistence in the external images are prone to strong systematics. The problem is that after few hundreds of seconds, the persistence signal is below $1e^{-s^{-1}}$. In the external exposures such signal sits on top of the sky background, thus the accuracy of the signal measurements depends on the ability of determining the sky with sufficient accuracy. Westerlund 1 is however an extremely crowded cluster (mass $\sim 10^5 M_\odot$, half-light radius of the order of 1 arcminute, half the size of the WFC3/IR detector), with a large number of bright sources as well as an extremely large number of unresolved ones. The bright sources should provide in principle the most useful stimuli for this study, given that they generate a persistence signal that could in principle be detectable above the sky level. They are however concentrated in the central region of the cluster thus, regardless of the fact that the externals
Figure 1: The full orbital sequence for visit 3, as visualized by the APT orbit planner, illustrating the relative timing of the different exposures.

are dithered with respect to each other, in many cases the pixel occupied by bright sources in the $j$-th exposure is later occupied by another source bright enough to make a persistence measurement impossible. This reduces the number of useful persistence measurements in the externals.

Furthermore, the unresolved light from the fainter stellar population in Westerlund 1 follows the density profile of the cluster and therefore has a gradient from the center of the cluster outwards, as visible in Figure 2. It is thus necessary to estimate the background level locally, not as an image-average, to ensure that the correct background flux is subtracted when measuring persistence in a pixel. This measurement requires defining an annulus small enough to be close to the pixel of interest, but large enough to include a sufficient number of pixels to reduce the random fluctuation of the mean sky measurements in the annulus. Given the high crowding, sigma clipping of the bright pixels is required to avoid including bright stars in the sky measurements. Our experiments show that the sky measurement is sensitive to the sky annulus size, distance from the pixel of interest, as well as the $\sigma$-level adopted for clipping. These systematics are of a level comparable with the strength of the persistence signal we are trying to measure. As a result, the systematic uncertainties in the sky measurement are too large to allow a robust determination of the persistence signal in these particular external observations. We thus reluctantly abandoned the external exposures in the final analysis of the persistence signal decay.

For completeness and illustration purposes, we include in this document a description of the procedure developed for measuring persistence in the externals. This procedure is quite general and not specific to this particular dataset. It may be useful in the future for similar studies of persistence in external exposures, with more suitable targets (i.e., where the background level measurements are less affected by systematic problems). Moreover, the same procedure, except for the background level measurement, is used for the darks, where our persistence measurements are much more robust.
4 Measuring persistence

One of the major differences of the current study with respect to previous analysis by the WFC3 team, is that instead of using the final calwf3 products (.flt files, i.e. the results of the up-the-ramp fit), we use the individual reads in the MULTIACCUM sequence (.ima files) to measure the persistence signal. This allows for a higher time cadence at the cost of noisier individual measurements. Moreover, the up-the-ramp fit procedure that produces the calibrated .flt files within calwf3 assumes that the signal has a constant flux (i.e. the accumulated signal grows linearly with time). Persistence is however a decaying signal, thus, for pixels containing persistence, the up-the ramp-fit hypothesis of constant flux is not satisfied. One could expect, in principle, that calwf3 should produce fit results equivalent to the ”time-averaged” persistence signal, i.e. \((C_e - C_s)/t_{\text{exp}}\), with \(C_e\) and \(C_s\) the charge at the end and start of the exposure, respectively and \(t_{\text{exp}}\) the total exposure time. In detail, however, the pipeline does not exactly compute the average because of several ”non-linear” steps such as cosmic ray rejection which can be triggered by fast-varying signals. For these reasons we use the accumulated counts directly, without trying to fit the count rate.

The construction of the persistence decay curve for our analysis follows these steps:

1. For each stimulus image we identify pixels within a given stimulus fluence range. This step involves using the .flt files, which are in units of \(e^- s^{-1}\), and are multiplied by their respective exposure times to get a fluence in \(e^-\). We note that, as long as the pixels are not saturated in the first read up the ramp, the calwf3 pipeline is able to estimate
a flux. The fluence that we obtain by multiplying the flux times the exposure time is proportional to the total photon flux during the exposure; it represents the total number of electrons that would be detected in an infinite-well pixel, not the actual number of generated photoelectrons which is of course limited by the total full well capacity.

2. We choose only pixels that were not exposed in earlier exposures to fluences larger than 20% of the fluence in the current exposure. This step also involved the .flt files.

3. To measure the persistence signal we proceed in two ways, according to whether the exposure is an external or a dark one. In both cases we use the .ima files which contain the set of individual reads.

   (a) Cluster exposures: for the selected pixels we ascertain whether any stars fall on them in each exposure following the stimulus. We use only the pixels that stay "star-free". To estimate the local sky value we use a circular annulus around the pixel of interest. All signal in excess of the sky is attributed to persistence. As previously noted, the uncertainty in this steps leads to unreliable persistence measurements in the external exposures, thus, in practice, we do not use them in the following analysis.

   (b) Dark exposures: computing the persistence signal in the dark exposures is easier. There is no need to check whether pixels are affected by stars, thus the persistence signal is simply the measured signal minus the dark signal. The latter is obtained from the reference files used in the data reduction pipeline and available via the HST Calibration Reference Data System, i.e. the superdarks for the appropriate read sequences. This is an accurate representation at short times, but at times longer than several thousands of seconds the fluctuations in the dark current become comparable to the persistence signal one wishes to measure. We note that the darks, which are usually provided by calwf3 in units of counts s$^{-1}$ are converted at this step into units of e$^{-1}$ s$^{-1}$, by multiplying them by the WFC3/IR gain. Each quadrant of the dark current image is multiplied by the corresponding ATODGNx keyword in the dark exposure header, with x∈[A,B,C,D]

4. The science extensions of the .ima FITS files produced by calwf3 contain an average flux corresponding to the total charge accumulated up to a certain read, $C_j$, minus the charge in the 0-th read, $C_0$, divided by the elapsed time, $t_j - t_0$.

$$IMA_j = \frac{C_j - C_0}{t_j - t_0}$$  \hspace{1cm} (2)

5. At this step, we convert the IMA with simple operations into the average flux between consecutive reads:

$$IMA'_j = \frac{C_j - C_{j-1}}{t_j - t_{j-1}} = \frac{IMA_j \times (t_j - t_0) - IMA_{j-1} \times (t_{j-1} - t_0)}{t_j - t_{j-1}}$$  \hspace{1cm} (3)

\footnote{CRDS, https://hst-crds.stsci.edu/}
which, after subtracting the background represents the average number of electrons per second produced by persistence between the \(j - 1\)-th and \(j\)-th reads. We note that the reads ordering in our nomenclature, \(...j - 1 \rightarrow j \rightarrow j + 1...\) corresponds to their temporal ordering. This differs from the .ima files that adopt an inverted convention, where the .ima[‘SCI’,1] FITS extension corresponds to the last read and the .ima[‘SCI’, NSAMPS] corresponds to the zero-th read. With an abuse of notation in this document we have mentioned or will sometimes mention that we use the .ima files or MULTIACCUM sequences to measure persistence; we however always imply that we use the .ima files modified according to equation (3) and reordered into a temporal sequence.

6. For persistence measured in the cluster exposures there is a further step. External exposures (as opposed to darks) are routinely flat-fielded by the calwf3 pipeline. The flat field files used during this operation incorporate a correction for distortion: due to the fact that the WFC3/IR camera is tilted with respect to the optical axis, different pixels "see" different total sky areas. This is the same for the flat field exposures. Dividing a science exposure by the flat field removes the geometric effect, thus preserving the flux for extended sources (i.e. a uniform surface brightness source has non-uniform counts in the raw images, but the non-uniformity is the same as in the flat fields and thus divides out). For point sources (like our persistence signal, which is localized in individual pixels), the flat fielding step introduces the reciprocal effect: identical point sources have the same counts in the .raw images but those counts are divided by different numbers when the image is flat-fielded. We thus remove this effect by multiplying the background-subtracted persistence signal with the pixel-area-map (PAM), an image containing the area ratios between each pixel and a reference pixel whose area is set to one\(^2\).

7. We create a database of persistence measurements from which it is possible to identify "individual ramps", i.e. persistence decay signals for single pixels, which are characterized by a single stimulus level and by "time elapsed since the end of the stimulus". This time is measured as the central time during the specific read interval, \(t_{\text{mid}} = 0.5 \times (t_i + t_{i-1})\), minus the end time of the stimulus exposure.

8. We group the stimuli by fluence levels, and then group the corresponding persistence signals in 5 second elapsed-time bins. We then compute the median of each bin to obtain the decay curve of the persistence. Each measurement along the persistence decay curve for individual pixels is characterized by \(t_{\text{mid}}\), and by interval width \(\delta t\), the time between the two reads. When averaging measurements from multiple pixels, grouped by \(t_{\text{mid}}\), measurements with different \(\delta t\) are grouped and averaged separately. We define the average measurement \(m_j(t_{\text{mid},j}, \delta t_j) \equiv < m(t_{\text{mid},i}, \delta t_i) >, \text{ for } t_{\text{mid},i} \in [t_{\text{mid},j-5}, t_{\text{mid},j+5}], \delta t_i = \delta t_j, \text{ and } i \in \mathcal{M}, \text{ the ensemble of the individual measurements.}

We note that the values of the mean persistence signal accumulated between two reads, as per equation (3), depend both on the time elapsed since the end of the stimulus and on

\(^2\)PAMS are available at http://www.stsci.edu/hst/wfc3/pam/pixel_area_maps for the WFC3 detectors
the difference in time between the \( j \)-th and \((j - 1)\)-th read. This easily seen if we consider an arbitrary elapsed time, \( t_* \), and two hypothetical pairs of reads bracketing such time, e.g. \((t_* - \frac{\delta t_a}{2}, t_* + \frac{\delta t_a}{2})\) and \((t_* - \frac{\delta t_b}{2}, t_* + \frac{\delta t_b}{2})\). If \( p(t) \) represents persistence, it easy to see that

\[
IMA_{ja}' = \frac{1}{\delta t_a} \times \int_{t_* - \frac{\delta t_a}{2}}^{t_* + \frac{\delta t_a}{2}} p(t) dt 
\]

\[
IMA_{jb}' = \frac{1}{\delta t_b} \times \int_{t_* - \frac{\delta t_b}{2}}^{t_* + \frac{\delta t_b}{2}} p(t) dt
\]

(4)

unless \( p(t) \) is a constant, which persistence is not. When modeling persistence between reads, the definition of average signal between two times highlighted in equation (4) must be taken into account for a correct comparison with the measurements given by equation (3).

5 Results

From this point onward we limit our analysis to persistence measured in the dark images, using as stimulus only the last external image. The preceding externals are used only to flag out pixels where there happened to be a source with fluence greater than 20% the fluence measured in that pixel in the last external. This way we remove the uncertainty due to repeatedly exposing a pixel to a strong stimulus.

For each fluence level we fit a power law model to the average persistence signal. We perform the average measurements, step 8) in Section 4, for each visit separately, as well as by grouping all visits together. This way we can measure effects due to different exposure times in the stimuli, at fixed fluence. Given that fluence = flux \( \times \) exposure time, at fixed fluence visits 1, 2 and 3 (for which the externals have 352, 499, 799 seconds exposure times, resp.) have progressively decreasing fluxes. Moreover, we perform fits by restricting the fit regime to 250, 1000, 4000 seconds after the stimuli. This way we can test whether the rate of decay of persistence changes with time. We indicate these 3 cases as the 250, 1000 and 4000 models respectively and indicate them with \( P_{250} \), \( P_{1000} \), \( P_{4000} \).

The persistence decay model is specified in terms of an instantaneous signal, \( p(t) = A t^\gamma \). In order to compare it with the measurements, we have to consider its average over the same time interval, \( p_j \equiv \int_{t_j - \frac{\delta t_j}{2}}^{t_j + \frac{\delta t_j}{2}} A t^\gamma dt \). Our fit consists in minimizing the quantity:

\[
\sum_{j \in <M>} (m_j - p_j)^2
\]

(5)

where \(<M>\) represents the ensemble of averaged measurements.

An example of the fit results is shown in Figure 3 for a fluence level of \( 3.2 \times 10^5 \) \( e^- \), i.e. \( 4 \times \) the average saturation level of a WFC3/IR pixel, \( \sim 80000 \) \( e^- \). Several features are worth noticing in this Figure. The first is that a straight line (in log-log space) is an overall good fit to the measurements down to the shortest times after stimulus probed, i.e. about 100 seconds. The individual measurements become quite noisy above 1000 seconds, but the overall linear trend is still visible. Another important feature is that the power law index becomes steeper as longer times after stimuli are considered. This can be seen in the figure by looking at how the slopes of the lighter color lines are steeper, while the darker color lines tend to be more horizontal (tending toward the reference slope of \( \gamma = -1 \)). This behavior
Average stimulus fluence = 3.2e+05 $e^-$

**Figure 3:** Persistence measurements and power law fit results for a fluence level of 320,000 $e^-$; the fluence values associated with the figures here and in Appendix A are the midpoints of 0.2 dex bins). Each row represents a visit, with the last one representing all visits combined. Each column represents a different value of the time between reads in the .ima files. The two rightmost columns do not have a superimposed best fit model line because there is only one measurement for those $\delta t$. Circles indicate the averaged measurements, while the solid lines represent the power-law fits. Each shade of color represents a different fit interval length, starting at 0 seconds after the end of the stimulus and ending at 250, 1000, 4000 s (lighter to darker, resp.). The ending points of the fit intervals are represented by vertical dashed lines of the same shade of color as the best fit solid lines. For ease of display, the measurements and the best-fit models are divided by a power law with $A = 300$ and $\gamma = -1$, giving the typical value of 0.3 $e^-$ s$^{-1}$ at 1000 seconds. This reference model would be a horizontal line at $y = 1$ in the plots. Rising lines correspond to power laws shallower than $\gamma > -1$, these decline slower than $\gamma = -1$, thus the ratio to the reference model is progressively larger. Declining lines (not present in this plot, but see Appendix) represent steeper power laws. For fixed $\gamma$ the vertical location of the lines represents their normalization value (e.g a model with $A = 600$ and $\gamma = -1$ would be a horizontal line with $y = 2$).

is repeated, on average, at all fluence levels (see Appendix for equivalent figures at different fluence levels).

Another way of summarizing the results is presented in Figure 4. In this figure we show three different summaries of the best fit models. In the top panel we show the persistence predicted by the best-fit model for 3 different fit intervals (250, 1000, 4000 seconds) evaluated at the end of the corresponding interval, and divided by the prediction of the best fit model obtained using a 250 seconds fitting time interval, evaluated at 250, 1000, and 4000 seconds respectively. By definition each line starts a t=250 s, $y = 1$. A downward trend in the
Persistence/P_{250} panels means that the 250 second model predicts more persistence than the 1000 and 4000 ones, thus the ratios are below one and decreasing. This also means that persistence is decaying faster at later times than what would be predicted by extrapolating the 250 second best-fit model. The general trend in the top panels, albeit with some noise, is for persistence to decay more rapidly as time progresses. Effectively, the 250 model predicts almost twice as much persistence at 4000 seconds than the 4000 seconds model.

In the central and lower panels, the rate of decay $\gamma$ and the normalization, $A$, are plotted separately. In terms of $\gamma$, we observe a steepening, or $\Delta \gamma$, of the order of 0.05 between the 250 and 4000 seconds models. The normalization factor, $A$, shows corresponding changes of 15%-30%.

Examination of the differently colored lines in the central series of panels in Figure 4 reveals a trend with exposure time. At fixed total stimulus fluence the slope measured in Visits 1, 2 and 3 is progressively shallower, independent of the elapsed-time interval adopted for the fit. This is apparent only for stimuli above the saturation level of the WFC3/IR pixels, that is persistence tends to decay more rapidly for Visit 1 stimuli than for Visit 3 when the stimulus is strong enough to expose all traps to free charge. A possible interpretation is that 1) the traps with the longest capture times are more easily filled in the exposures where saturation is maintained for longer times, i.e. those in Visit 3, and 2) the release times are proportional to the capture times, therefore it both takes longer to fill these traps, and they also release their electrons more slowly, thus the slower rate of decay for persistence measured in Visit 3. This behavior is consistent with that seen in other investigations (Long et al., 2015a).

6 Summary and Conclusions

We have studied the decay of persistence in WFC3/IR images at short time intervals, using images of the Westerlund 1 cluster, followed by dark exposures. To improve our sensitivity to short time delays we have used the MULTIACCUM sequences recorded in the .ima files. These provide both a better time sampling of the persistence signals as well as bypass the problematic assumption of the calwf3 pipeline when performing the up-the-ramp fit that produces the calibrated .flt products, i.e. that all signals rates are constant in time. We fit the measured persistence signal with a power law model. Overall a power law is a good description of the data in the 100-5000 seconds after the end of the stimulus. By varying the time window over which the fit is performed it is however possible to detect a consistent steepening trend in the power law slope as time progresses. In other words, persistence is observed to decay more slowly at shorter times than at longer ones. This type of behavior is expected, given that a steep trend cannot continue down to very short times, where a negative power law slope would be unphysical. We speculate that the detected flattening or tapering-off of the power-law at the shortest times probed by our observations may in fact continue at even shorter ones, as expected by a model of persistence with a finite number of traps.

The original design of the 14016 calibration program used in the present work was intended to allow measurements of persistence in external exposures as well. We found however that the very high crowding in Westerlund 1 does not allow us to measure the local back-
Figure 4: Summaries of the best fit results for power law fits to the measured persistence signal as a function of elapsed time and for different stimulus fluence levels. Each color corresponds to a different visit. Top: persistence predicted by fitting the signal up to 250, 1000, 4000 s after the stimulus, evaluated at the end of the respective interval (e.g. $P_{1000}$ is only evaluated at 1000 seconds), divided by $P_{250}$ evaluated at the same times. Center: power-law index value for the $P_{250}$, $P_{1000}$, $P_{4000}$ models. Bottom: power-law normalization for the $P_{250}$, $P_{1000}$, $P_{4000}$ models.
ground level with a precision sufficient to measure the weak persistence signal on top of the spatially varying sky background. We thus utilized only the dark exposures for our persistence measurements reported in the present work. The code we have developed is, however, designed to handle persistence in externals as well, and thus a future development of the current analysis could be to apply the same methodology to existing suitable archival or future data.

**Appendix A  Persistence fits for different fluence levels**

Each figure in this section is the same as Figure 3, but for a different stimulus fluence level. We bin the log(stimuli) in 0.2 dex bins, starting at 4.6 (fluence of 40,000 $e^-$, or half the typical WFC3/IR full well capacity). The fluence value associated with each figure is the mid-point of the respective bin. For a complete description of the content of the Figures in this section, see the caption of Figure 3.

![Persistence fits for different fluence levels](image)

Figure 5
Average stimulus fluence = $7.9 \times 10^4$ e $^{-}$

Time since end of stimulus [s]

Persistence/P$_{ref}$

VIS1

VIS2

VIS3

ALL

Figure 6

Average stimulus fluence = $1.3 \times 10^5$ e $^{-}$

Time since end of stimulus [s]

Persistence/P$_{ref}$

VIS1

VIS2

VIS3

ALL

Figure 7

14
Average stimulus fluence = $2.0 \times 10^5 \text{ e}^-$

Figure 8

Average stimulus fluence = $5.0 \times 10^5 \text{ e}^-$

Figure 9
Average stimulus fluence = $7.9 \times 10^5 e^{-}$

**Figure 10**

Average stimulus fluence = $1.3 \times 10^6 e^{-}$

**Figure 11**
Average stimulus fluence = 2.0e+06 e^- 

![Figure 12](image2.png)

Average stimulus fluence = 3.2e+06 e^-

![Figure 13](image3.png)

Persistence/P_{ref}
Average stimulus fluence = $5.0 \times 10^6$ e$^-$

![Figure 14](image1)

Average stimulus fluence = $7.9 \times 10^6$ e$^-$

![Figure 15](image2)
References

Dressel, L., & the WFC3 team. 2017, WFC3 Instrument Handbook v. 9.0


—. 2015a, Persistence in the WFC3 IR Detector: an Improved Model Incorporating the Effects of Exposure Time, Tech. rep.


