AGES OF STAR CLUSTERS IN THE TIDAL TAILS OF MERGING GALAXIES

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ABSTRACT

We study the stellar content in the tidal tails of three nearby merging galaxies, NGC 520, NGC 2623, and NGC 3256, using \textit{BVI} imaging taken with the Advanced Camera for Surveys on board the \textit{Hubble Space Telescope}. The tidal tails in all three systems contain compact and fairly massive young star clusters, embedded in a sea of diffuse, unresolved stellar light. We compare the measured colors and luminosities with predictions from population synthesis models to estimate cluster ages and find that clusters began forming in tidal tails during or shortly after the formation of the tails themselves. We find a lack of very young clusters ($\leq 10$ Myr old), implying that eventually star formation shuts off in the tails as the gas is used up or dispersed. There are a few clusters in each tail with estimated ages that are older than the modeled tails themselves, suggesting that these may have been stripped out from the original galaxy disks. The luminosity function of the tail clusters can be described by a single power-law, $dN/dL \propto L^\alpha$, with $-2.6 < \alpha < -2.0$. We find a stellar age gradient across some of the tidal tails, which we interpret as a superposition of (1) newly formed stars and clusters along the dense center of the tail and (2) a sea of broadly distributed, older stellar material ejected from the progenitor galaxies.

Key words: galaxies: interactions – galaxies: star clusters: general – galaxies: star clusters: individual (NGC 520, NGC 2623, NGC 3256) – galaxies: star formation

Supporting material: machine-readable table

1. INTRODUCTION

Tidal tails form during the interaction between galaxies, and are composed of stars, gas, and dust ejected from the original galactic disks. These interactions are often accompanied by one or more bursts of star and cluster formation in the main bodies of the parent galaxies, according to simulations (e.g., Mihos et al. 1993) and observations of star clusters (e.g., Whitmore & Schweizer 1995).

The star cluster formation processes that occur within tidal tails, however, are not well understood. For example, building on pioneering work by Knierman et al. (2003), Mullan et al. (2011, hereafter M11) used $V$ and $I$ band photometry from Wide Field Planetary Camera 2 on the \textit{Hubble Space Telescope} (\textit{HST}) to measure the brightness and colors of point-like sources both in and out of the tail region for 23 tidal tails. They found a statistically significant number of clusters in 10 out of their 23 tails, and they concluded that the presence of tidal clusters depends on several factors, including tail age, $H_\text{I}$ density, and surface brightness of the tail. In this work we revisit two of these tails using higher quality data taken with the Advanced Camera for Surveys (\textit{ACS})\textsuperscript{3} on \textit{HST}/Wide Field Camera (\textit{WFC}) and detect clusters in both of them for the first time.

Even less is known about the ages of star clusters in tidal tails. de Grijs et al. (2003) found $\sim 40$ clusters each in the Tadpole galaxy with rough ages of $175 \pm 25$ Myr and in the Mice galaxies (NGC 4676) with ages $\approx 100 \pm 20$ Myr. Most of these clusters appear to have formed in the tails since their estimated ages are younger than those of the tails; de Grijs et al. estimated a dynamical age of $400–800$ Myr for the Tadpole, and Privon et al. (2013) suggested a formation time of $\sim 175$ Myr ago for the Mice. Tran et al. also observed the Tadpole galaxy, and found 42 extremely young tail clusters ($\sim 4–5$ Myr; 2003). Bastian et al. (2005) found young massive star clusters in the tails of NGC 6872 and were able to estimate ages and masses for individual clusters using \textit{UBVI} and $H_\alpha$ photometry. No star clusters older than the dynamical age of the tidal tail were found (at least down to their completeness limit of $M_\text{V} = -10.4$), once again suggesting that the clusters formed from the tidal debris. They also found a large population of clusters that are very young ($< 10$ Myr). While looking for spatial trends, Bastian et al. found that older tail clusters tend to be located closer to the main bodies, while younger clusters are spread throughout the tail. They argue that these findings suggest an initial burst of cluster formation as the tails form. After this burst, as the tails expand, the gas clouds cool and condense, eventually becoming sites of individual cluster formation.

While tidal tails provide a unique and interesting environment to study star clusters, they also provide key information for improving simulations of interacting/merging galaxies. Efforts to reproduce mergers using simulations focus on tidal tail morphology to constrain details of the galaxy interaction. Ages of star clusters in tails provide constraints on the merger timescale. The spatial distributions of clusters in the main bodies and tails helps to discriminate between different prescriptions for star formation within the simulations. For example, dynamical models of the interacting system NGC 7252 show that density-dependent star formation results in a more centrally concentrated distribution of main-body clusters, while shock-induced star formation tends to spread cluster formation throughout the galaxy, including in the tails (Chien & Barnes 2010).

The goal of this work is to better understand how clusters form and are distributed during the merging of two galaxies. We focus our study on three merging systems, NGC 520, NGC 2623, and NGC 3256. This paper is set up in the following

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\textsuperscript{3} \url{http://www.stsci.edu/hst/acs}
manner. In Section 2 we discuss the observations and photometry, as well as cluster selection. Section 3 presents the cluster densities and cluster luminosity functions, as well as colors and ages of clusters and of the diffuse light. In Section 4 we discuss the galaxy merger history and interpret our results. Section 5 summarizes the work and presents conclusions.

2. OBSERVATIONS, DATA REDUCTION, AND CLUSTER SELECTION

2.1. Observations and Data Reduction

Observations of NGC 520 and NGC 2623 were taken with the WFC on the ACS on HST as part of program GO-9735 (PI: Whitmore). NGC 520 was observed in 2004 October using the filters F435W (∼B in the Johnson–Cousins system; exposed for 2400 s), F555W (∼V; 1000 s), and F814W (∼I; 1200 s). The entire galaxy, including the majority of its tidal tails, was covered in a single WFC frame. Observations of NGC 2623 were taken in 2004 February using the same filters with exposure times of 3730, 1206, and 2460 s, respectively. It was also covered in a single WFC frame. Images of NGC 3256 come from two separate observing proposals. F555W filter observations of NGC 3256 were obtained in 2003 November as part of the program GO-9735 (2552 s). WFC observations using F435W and F814W filters were taken in 2005 November as part of program GO-10592 (PI: Evans) for 1320 and 760 s, respectively. Both fields cover most of NGC 3256’s eastern tail, as well as its main body. Figure 1 shows the WFC fields of view used in this study.

The raw data were processed through the standard ACS pipeline. The reduced, multidrizzled images were taken from the Hubble Legacy Archive and have a scale of 0″05 per pixel. Figure 2 shows F814W images of our targets, with the tidal tail portions studied in this work labeled. We will refer to specific tails within a galaxy by abbreviating the location of each tail (i.e., the northern tail of NGC 520 will be called NGC 520N). We define the tail edges as the locations where the counts drop to 3σ above the general background level.

Figure 2 shows that NGC 520 has two tidal tails, commonly referred to as the north and south tails. Both of these tails extend beyond the field of view in Figure 2. Not seen in Figure 2 is the dwarf galaxy UGC 957, at about 6′ north–west of NGC 520. NGC 2623 is in the middle panel of Figure 2. It exhibits two nearly symmetric tidal tails, although the northern tail is wider than the southern tail. An extremely bright, triangle-shaped region south of the nucleus of the galaxy, which we call the pie wedge, is also highlighted. NGC 3256 is on the right in Figure 2. While it has two tails (east and west), only part of the eastern tail was observed. The three mergers are next to each other on the Toomre Sequence, in the order NGC 520, NGC 2623, and NGC 3256 (Toomre 1977). General properties of these systems are listed in Table 1.

2.2. Cluster Selection

Star cluster candidates were found by running the IRAF task DAOFIND on the I band images. A few thousand objects were detected in each galaxy. We perform BVI aperture photometry on all sources in NGC 520 and NGC 3256 using an 4 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under a cooperative agreement with the National Science Foundation.
aperture size of 3 pixels in radius and a background area of radii 8–11 pixels using the IRAF task PHOT. Because of the greater distance to NGC 2623, we use a smaller aperture of 2 pixels (with the same background area) in order to minimize contamination from nearby sources. In the pie wedge region, we estimate the background level using annuli between 5–8 pixels, in order to minimize the impact of crowding. Magnitudes were converted to the VEGAMAG system using zeropoints calculated from the ACS zeropoint calculator. Aperture corrections were performed in NGC 3256 by selecting the brightest ∼20 isolated clusters in each filter and finding their mean 3–10 pixel magnitude difference. We then applied the 10 pixel to infinity aperture corrections taken from the encircled energy catalog for ACS/WFC in Table 3 of Sirianni et al. (2005). The final corrections were 0.45, 0.42, and 0.54 magnitudes for $B$, $V$, and $I$, respectively, and they were applied to each cluster. Unfortunately, the background level was too high in NGC 520 and NGC 2623 for reliable aperture correction determinations. We find that clusters in NGC 520 have a similar range of sizes as those in NGC 3256 and therefore applied the aperture corrections derived from NGC 3256 to the NGC 520 clusters. Clusters in the more distant NGC 2623 are nearly indistinguishable from point sources; we assume the 2 pixel to infinity aperture corrections from Table 3 of Sirianni et al. (2005).

We measure FWHM values for all detected sources using the ISHAPE software (Larsen 1999). ISHAPE measures FWHMs by convolving the point-spread function with a King profile, then performing a $\chi^2$ calculation to test the goodness of fit to each individual cluster (King 1966). ISHAPE iterates through different values for the effective radius until a minimum $\chi^2$ is found.

We select cluster candidates using a combination of automated selection criteria (listed in Table 2) and visual inspection of each candidate (see Bastian et al. 2012). The selection criteria in $m_V$, FWHM, and magnitude error ($\sigma_V$) remove most foreground stars and background galaxies. We made a cut at the bright end of $m_V = 20$, in order to eliminate saturated foreground stars (brighter than any cluster expected in these mergers). The faint end of our cluster catalog likely suffers from incompleteness. We restrict our sample to luminosities brighter than the point where the luminosity function (discussed in Section 3.2) turns down rather than continuing to increase in a power-law fashion. We use cuts in FWHM ($\text{size}$) to separate stars and background galaxies from clusters, to the highest degree possible. In NGC 3256, we exclude sources with FWHM values less than 0.2 pixels, because the FWHM of the vast majority of likely field stars was measured to be smaller than that value. We also place an upper limit of 2.0 pixels in FWHM to exclude very extended background galaxies. The lower limit on FWHM for clusters in NGC 520 was chosen to be 0.1 pixels because there is a group of young, compact clusters in the northern portion of NGC 520 S. At the distance of NGC 2623, clusters are essentially point sources, so FWHM measurements cannot distinguish clusters from bright, individual stars. Therefore, in addition to an upper limit on FWHM of 2.0, we apply a cutoff in magnitude uncertainty, $\sigma_V$. In the tails, $\sigma_V < 0.1$ did a good job removing obvious non-clusters, but in the pie wedge, we relax our $\sigma_V$ cut to 0.2 because the area is more crowded and has a very bright background.

Finally, we visually inspect each cluster candidate. For each galaxy we identify high signal-to-noise ratio ($S/N$) clusters, as well as obvious foreground stars, as benchmarks for fainter objects. We choose clusters based on their fuzzy appearance, as well as wider radial profiles than those of stars. Figure 3 shows three of the brightest clusters from each galaxy’s tidal tails, and Figures 4–7 show locations of clusters in each tail. All possible clusters were identified independently of the selection cuts listed above, then later compared to the sample obtained from the selection cuts. We find excellent agreement between the two methods in NGC 520 and NGC 3256, and we only include sources that both fit our selection cuts and visually appear as clusters. Due to the poor $S/N$ in NGC 2623, several sources appeared visually as likely clusters but had FWHM and/or $\sigma_V$ values outside of the selection criteria. Because of this low $S/N$, we rely more heavily on visual inspection than selection cuts and include some sources with FWHM or $\sigma_V$ values outside of the cuts. The total number of clusters found in each tidal tail ($N_{\text{clus}}$) is compiled in Table 3, and we compile the cluster catalog in Table 4.

Distant, red spheroidal galaxies can have a similar color and appearance to compact star clusters. To assess the possible contamination from background galaxies, we examine the colors and locations of sources that made it through our automated cuts, but are located outside of the tidal tail regions, with the reasonable expectation that most of these are likely background galaxies. However, we find no such objects in any of our fields, only extended, obvious background galaxies. In addition, many background galaxies should appear elliptical rather than circular. Using ISHAPE, we measure the ellipticity of each cluster candidate and find few elongated red sources. We conclude that the fraction of background galaxies that have made it through our cluster selection criteria is negligible.

### Table 1

| Galaxy      | R.A.   | Decl.  | Distance Modulus$^a$ | $A_V$ | $E(B-V)$ | $E(V-I)$ |
|-------------|--------|--------|----------------------|-------|----------|----------|
| NGC 520     | 01 24 35.1 | +03 47 33 | 32.46                | 0.077 | 0.025    | 0.035    |
| NGC 2623    | 08 38 24.1 | +29 45 17 | 34.50                | 0.113 | 0.036    | 0.051    |
| NGC 3256    | 10 27 51.3 | -43 54 13 | 32.79                | 0.334 | 0.107    | 0.151    |

$^a$ Distance moduli come from distances obtained from recession velocity measurements relative to the local group, adopting $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

### Table 2

| Galaxy      | $m_V$ | FWHM  | $\sigma_V$ |
|-------------|-------|-------|--------|
| NGC 520     | 25.0  | 0.1–2.0 | ...   |
| NGC 2623    | 26.5  | ≤2.0   | 0.1    |
| pie wedge   | 26.5  | ≤2.0   | 0.2    |
| NGC 3256    | 26.0  | 0.2–2.0 | ...   |

http://www.stsci.edu/hst/acs/analysis/zeropoints
3. RESULTS

We find a population of star clusters in each tidal tail in our sample of galaxy mergers. In this section we present the spatial densities, luminosities, and colors of clusters in each tidal tail and estimate their ages.

3.1. Cluster Density

One quantitative measure of a cluster population is its surface number density, which is often used when cluster selection must be done statistically. We measure the number density of clusters, \( \Sigma_{\text{clus}} \) (clusters kpc\(^{-2} \)), for each tidal tail based on the catalogs in this work. We choose a magnitude cutoff of \( M_V \approx -8.5 \) (see Section 3.2 for details on absolute magnitude calculation) to directly compare our results to those of M11 (although altering the cutoff to \( M_V = -8.0 \) and \(-9.0 \) yields qualitatively similar results). NGC 520 S yielded \( \Sigma_{\text{clus}} = 0.49 \), while NGC 520 N yielded \( \Sigma_{\text{clus}} = 0.0 \) because its five clusters were all fainter than \( M_V \approx -8.5 \). The pie wedge in NGC 2623 possesses the highest cluster density in our sample by over an order of magnitude at \( \Sigma_{\text{clus}} = 8.5 \), while the north and south tails yielded \( \Sigma_{\text{clus}} = 0.54 \) and 0.32, respectively. Lastly, NGC 3256 E possessed a relatively low density of \( \Sigma_{\text{clus}} = 0.10 \). We find that while all tidal tails in our sample contain clusters, there is a large variation in \( \Sigma_{\text{clus}} \) for each tail.

For both NGC 520 and NGC 3256, we are able to directly compare our values of \( \Sigma_{\text{clus}} \) to those values found in M11, although we note that we cover different areas of the tails for both systems. We also note that we adopt slightly different distance moduli than M11, resulting in small differences in \( \Sigma_{\text{clus}} \). M11 found \( \Sigma_{\text{clus}} = -0.011 \pm 0.013 \) in NGC 520 N and \( \Sigma_{\text{clus}} = 0.004 \pm 0.082 \) for NGC 3256 E, both of which are consistent with zero. While our results for NGC 520 N agree with M11, we find a clear population of clusters in NGC 3256 E brighter than \( M_V \approx -8.5 \). M11 also measured \( \Sigma_{\text{clus}} \) for \( M_V \approx -7.5 \) and \( M_V \approx -6.5 \), however we do not compare \( \Sigma_{\text{clus}} \) values at these cutoffs due to incompleteness. We find that, in general, younger tails tend to exhibit higher \( \Sigma_{\text{clus}} \), in agreement with the results of M11.

3.2. Luminosity Functions (LFs)

The LFs of the tail clusters are shown in Figure 8. These can be described by a power law, \( dN/dL \propto L^\alpha \), where \( \alpha \) is determined from a linear fit to \( \log(dN/dL) \) vs \( \log(L) \). We fit our cluster LFs over the \( V \) band magnitude range which we believe to be reasonably complete. Magnitudes include distance moduli from Table 1 as well as aperture corrections, and they have been dereddened because of foreground extinction (see Section 3.3.1). We are unable to measure the LFs in NGC 520 N and NGC 2623 S because they contained too few clusters.

We determine the LFs in two different ways, using both a fixed magnitude bin width (denoted \( \alpha_{\text{const-mag}} \)) and a fixed number of clusters per bin (\( \alpha_{\text{const-num}} \)). The results from both methods are consistent, and we report \( \alpha \) values for the latter because it is better at handling low number statistics. In all cases, however, we find that the two values for \( \alpha \) are the same, within the uncertainties. The typical standard deviation among \( \alpha \) calculated using \( B \), \( I \), and \( V \) band magnitudes is \( \approx 0.13 \), with no systematic trend. The LFs in the \( B \) and \( I \) bands have similar slopes to those in the \( V \) band.

In NGC 520 S, we find a best fit of \( \alpha \approx -2.32 \pm 0.36 \) down to \( M_V \approx -8.0 \). We restrict our fit to this magnitude limit because completeness becomes an issue fainter than this. For NGC 2623, we focus on the pie wedge and northern tail. We fit the luminosity function in both regions down to \( M_V \approx -9.0 \), and find \( \alpha = -2.39 \pm 0.34 \) for the northern tail and \( \alpha = -2.02 \pm 0.21 \) for the pie wedge. The luminosity function in NGC 3256 E is best fit with \( \alpha = -2.61 \pm 0.27 \) down to \( M_V = -8.0 \).
We find no evidence for a deviation from a simple power-law at the bright end of the LF in any of our tail regions. Several studies have shown that the luminosity function can range from $-2.8 < \alpha < -1.9$ for clusters in a variety of environments (e.g., Whitmore et al. 2014). We find that our results for $\alpha$ are within this range.

3.3. Colors and Ages of Clusters in Tidal Tails

We present the color–color diagrams for clusters in all tails in Figure 9. The color coding corresponds to different tails within each merging system. We also show with blue symbols the median $V - I$ and $B - V$ colors of clusters that apparently formed after the tidal tails (we assume tail ages from simulations that are discussed in Section 4.1 and compiled in Table 3). The solid line in each panel in Figure 9 is a stellar population model from G. Bruzual & S. Charlot (2006, private communication, hereafter BC06; and see also Bruzual & Charlot 2003) which predicts the evolution of star clusters from about $10^6$–$10^{10}$ yr. All models assume a metallicity of $Z = 0.02$, and a Salpeter (1955) initial mass function. Numbers mark the logarithmic age ($\tau$) corresponding to the population.

3.3.1. The Impact of Internal Reddening on Cluster Colors

In order to accurately age-date star clusters, we must understand how reddening affects their measured colors. We correct each cluster for foreground reddening of the Milky Way by using $A_{\lambda}$ values given in the NASA/IPAC Extragalactic Database, which are compiled in Table 1. The reddenings were estimated with the standard relations between them and the extinction. A reddening vector for $A_V = 1$ is shown in Figure 9 by the red arrow. The reddening vector is nearly parallel to the predicted evolution of cluster colors, making it challenging to disentangle the effects of age and reddening in the measured colors. For example, a young cluster with some extinction will have the same colors as an older cluster with no reddening.
Figure 9 shows that the clusters in each tail have a measured color spread. In principle, there are a few reasons this spread could exist other than photometric uncertainties, such as internal (and therefore differential) extinction or a range in cluster ages. Below, we examine each galaxy individually and determine that internal extinction does not greatly affect the majority of our cluster colors.

We first focus on NGC 2623, whose color distributions are shown in the upper- and lower-right panels of Figure 9. The spread in measured colors is the smallest for any tail studied here, and instead of spreading along the reddening vector, the cluster colors are fairly isotropically distributed. This pattern suggests that photometric uncertainties are primarily responsible for the color spread. We confirm this by creating color–color diagrams of NGC 2623 clusters in different $M_V$ bins, and while the cluster color spread increases with fainter magnitudes, the color distribution is centered near the median colors quoted in Table 3, regardless of brightness. If all of the clusters in the tails of NGC 2623 formed at the same time, clusters obscured by dust would exhibit redder colors than unobscured clusters, causing a color spread along the reddening vector. The clusters in both tidal tails of NGC 2623 appear to have formed over a relatively short period of time. This is also true in the pie wedge, where the narrow color ranges are also indicative of coeval cluster formation.

NGC 520 and NGC 3256, on the other hand, both exhibit a spread in color along the reddening vector. Here, we use the relative locations of blue ($B - V < 0.3$) versus red ($B - V \geq 0.3$) clusters, shown in Figures 10 and 11, to assess whether age or reddening are more likely to be responsible for the observed spread in color. In the case of NGC 520 (Figure 10), the bluer clusters tend to trace out the central, densest portion of the tail, while the redder clusters are more evenly spread throughout the tail. Reddening due to dust would be expected to give the opposite trend, with reddened clusters mostly near the center of
the tail. Figure 11 shows the locations of blue versus red clusters for NGC 3256. No obvious pattern is observed, but there is no evidence that red sources are primarily found in the brightest, densest portion of the tail. These results support the interpretation that the larger color spread of the clusters in the tails of NGC 520 and NGC 3256 is primarily due to a spread of cluster ages rather than to varying amounts of cluster reddening.

We now compare the colors of red tail clusters to clusters in the halos of NGC 520 and NGC 3256, which are shown in Figure 12. Selection and photometry of the halo clusters are performed using the same methods as in Section 2. We conclude that they are fairly similar in color, and therefore the red tail clusters are likely to be clusters that formed before the tails but were swept out during the tail formation. We will study these halo clusters and other main body clusters in more detail in a forthcoming paper. All of this evidence supports the interpretation that the red sources are older, unobscured star clusters.

### 3.3.2. Ages

We obtain ages for each cluster candidate by mapping their $B - V$ and $V - I$ colors to the BC06 track and finding the closest

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**Figure 7.** NGC 3256 E cluster candidates.

**Table 3** Properties of Star Clusters

| Galaxy  | Tail  | $\tau_{\text{tail}}$ (Myr) | $N_{\text{clus}}$ | $\Sigma_{\text{clus}}$ (kpc$^{-2}$) | $\tau_{\text{clus}}$ (Myr) | $\langle B - V \rangle$ | $\langle V - I \rangle$ | $\alpha$ |
|---------|------|-----------------|----------------|----------------|----------------|----------------|----------------|------|
| NGC 520 | north | 300 | 5 | 0.00 | 100 | 0.08 ± 0.05 | 0.38 ± 0.05 | ... |
| NGC 520 | south | 300 | 93 | 0.49 | 260 | 0.19 ± 0.09 | 0.60 ± 0.17 | −2.32 ± 0.36 |
| NGC 2623 | north | 220 | 75 | 0.54 | 230 | 0.10 ± 0.15 | 0.48 ± 0.28 | −2.39 ± 0.34 |
| NGC 2623 | south | 220 | 18 | 0.32 | ... | 0.12 ± 0.13 | 0.43 ± 0.17 | ... |
| NGC 2623 | pie wedge | ≤220 | 76 | 8.5 | ≥260 | 0.05 ± 0.15 | 0.43 ± 0.19 | −2.02 ± 0.21 |
| NGC 3256 | east | 450 | 141 | 0.10 | ≥260 | 0.21 ± 0.12 | 0.58 ± 0.21 | −2.61 ± 0.27 |

**Note.** $\tau_{\text{tail}}$ (Myr) is the predicted age of the tidal tail as estimated from simulations. $N_{\text{clus}}$ is the total number of clusters found in the region. $\Sigma_{\text{clus}}$ is the star cluster density per kpc$^2$ where $M_V < -8.5$. $\tau_{\text{clus}}$ (Myr) is the approximate age of the bulk cluster formation. Median colors ($\langle B - V \rangle$, $\langle V - I \rangle$) are for clusters younger than the age of the tidal tail. $\alpha$ values (from the relation $dN/dL \propto L^\alpha$) listed come from the $\alpha_{\text{const-num}}$ method.

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**Table 4** Cluster Catalog

| Tail ID | R.A. | Decl. | $m_B$ | $\sigma_B$ | $m_V$ | $\sigma_V$ | $m_I$ | $\sigma_I$ | $\tau$ |
|---------|------|------|-------|-----------|-------|-----------|-------|-----------|------|
| 520 N 1 | 1 124 31.77 | +3 47 59.03 | 24.68 | 0.02 | 24.01 | 0.03 | 22.82 | 0.02 | 9.11 |
| 520 N 2 | 1 124 31.02 | +3 48 3.70 | 24.63 | 0.03 | 24.47 | 0.04 | 24.10 | 0.04 | 8.06 |
| 520 N 3 | 1 124 32.06 | +3 48 6.88 | 25.82 | 0.07 | 24.70 | 0.05 | 23.41 | 0.03 | 9.99 |
| 520 N 4 | 1 124 29.58 | +3 48 27.96 | 24.31 | 0.02 | 24.23 | 0.03 | 23.85 | 0.03 | 8.06 |
| 520 N 5 | 1 124 28.77 | +3 48 35.25 | 24.41 | 0.02 | 24.33 | 0.03 | 23.88 | 0.03 | 8.06 |
| 520 S 1 | 1 124 36.18 | +3 45 37.42 | 24.95 | 0.03 | 24.56 | 0.04 | 23.76 | 0.03 | 8.76 |
| 520 S 2 | 1 124 36.27 | +3 45 38.32 | 25.14 | 0.03 | 24.40 | 0.04 | 23.20 | 0.02 | 9.30 |
| 520 S 3 | 1 124 35.59 | +3 45 41.18 | 25.00 | 0.03 | 24.94 | 0.05 | 24.34 | 0.04 | 7.59 |
| 520 S 4 | 1 124 36.11 | +3 45 43.04 | 23.66 | 0.01 | 23.25 | 0.02 | 22.46 | 0.01 | 8.81 |

**Note.** Apparent magnitudes ($m_\lambda$) and photometric errors ($\sigma_\lambda$) are listed, as well as individual cluster ages in log years ($\tau$).

(This table is available in its entirety in machine-readable form.)
match (Figure 9). Ages are fairly accurate in the range $10^6 < \tau < 10^9$ yr. Based on the discussion in Section 3.3.1, we assume no internal reddening.

Figure 9 implies that star clusters in the tails of NGC 520 and NGC 3256 have a broad range of ages up to $\sim 10^{9.5}$ yr. The tail ages are marked for each system with a red diamond, and clusters with colors below the red diamond are older than the tail age and might be old disk clusters that predate the merger; we will hereafter refer to these as "old" clusters, and we will refer to clusters younger than the tail age as "young" clusters.

The tail clusters in NGC 2623 contain ages up to a few $\times 10^8$ yr. The lack of observed clusters with ages older than a few $\times 10^8$ yr may simply be because they are too faint to be observed in our data at the distance of NGC 2623.

3.4. Diffuse Light in Tidal Tails

In addition to distinct stellar clusters, we also study the diffuse stellar light in the tails. Because the tidal tails form from material stripped from the native disks, this diffuse light should consist of a mixture of old disk stars, faint newly formed stars, and dissolved clusters. While individual stars are unresolved, the integrated colors of the diffuse light can help to constrain the age of the stellar populations (e.g., Gallagher et al. 2010). The light will be dominated by the brightest and youngest unresolved objects, so we expect that our age estimates will be lower limits.

We create color images: $B - V$, $V - I$, and $B - I$ for all three galaxies, and we show the $B - I$ images in Figure 13. The images were boxcar-smoothed with a 4 pixel kernel width. The main bodies of the mergers are very red because they contain large amounts of dust. The tidal tails are easily seen in Figure 13 as bluer regions where internal extinction is low (except, perhaps, in NGC 520 N, as also suggested by our analysis of clusters in Section 3.3.1). We therefore assume that colors in the tail regions are not greatly affected by internal extinction, and we believe diffuse light colors trace the ages of stellar populations relatively well.

We measure the $V - I$ and $B - V$ colors in different tail regions (white boxes in Figure 13 labeled from "A" up to "E" for each tail) after subtracting the point sources. Colors are calculated from the ratio of fluxes on a pixel by pixel basis and corrected for differences in instrumental zeropoints and foreground extinction. The diffuse light regions were chosen to cover most of the optically bright portions of the tails while avoiding breaks in field coverage and saturated foreground stars. The values in Table 5 are the mean color for each region. Figure 14 plots these values on a color–color diagram overlaid with the BC06 track. Figure 13 reveals that the diffuse stellar light in all tidal tails in our sample exhibits a common pattern (with the exception of NGC 3256 E). While the tidal tails are fairly blue ($B - I \leq 1.4$), we find that there is a gradient with $B - I$ color; it is redder near the edges of the tail and bluer near its axis. As previously discussed, this is not likely a reddening effect, so we believe that we are observing a gradient in the mean ages of the stars across these tails. In Section 3.3.1 we discussed the tendency for younger clusters to be near the center of the tail axis, leaving mostly
older clusters along the tail edges, especially in NGC 520 S. The diffuse light images further support a lack of young stars near the edges of the tails. We believe this to be the first time such a gradient across the tails has been observed in these galaxies.

Figure 14 reveals that the northern tail of NGC 520 has the reddest diffuse light of any tail in our sample. This is likely due to dust, as the red $B - I$ color in Figure 13 extends from the main body straight through the tail. Region A in the southern tail is also almost certainly affected by dust. We believe that the colors of the diffuse light in the other regions of the southern tail are dominated by ages of the underlying populations and

Figure 9. Color–color diagrams. Clusters have been corrected for foreground reddening of the Milky Way by using the $A_V$ values compiled in Table 1. Solid black lines are BC06 cluster evolution tracks, and numbers represent log ages of clusters. The reddening vectors are shown by the red arrows for $A_V = 1$. For comparison, the red diamond marks where the tail age ($\tau_{\text{tail}}$) would fall on this diagram based on the ages shown. Clusters that formed in the tail are younger than the tail and presumably fall above the red diamond on the track. The median colors of these young clusters are marked in blue, represented by either a square (northern/eastern tail), triangle (southern tail), or a cross (pie wedge). The points in the upper right-hand corners indicate typical errors from photometric uncertainties.

Figure 10. Southern tail of NGC 520. Red and blue circles indicate clusters that are redder and bluer than our color cut ($B - V = 0.3$), respectively.

Figure 11. Eastern tail of NGC 3256. Red and blue circles indicate clusters that are redder and bluer than our color cut ($B - V = 0.3$), respectively.

Figure 12.
We note that the diffuse light in the pie wedge Region NC, however, is bluer and yields an age of colors consistent with stellar populations of ∼700 Myr old. Region P, however, is bluer and yields an age of ∼500 Myr. We note that the diffuse light in the pie wedge (region P) has $B - V$ and $V - I$ colors close to region NC, as seen in Table 5, which might provide clues to its formation, as we discuss further in Section 4.1.2.

Figure 14 shows that the diffuse light in NGC 3256 is perhaps the most peculiar of our sample. Only region EC falls near the BC06 track, with an associated age $\tau \approx 650$ Myr. This would indicate that the diffuse light population in region EC is similar to the majority of the diffuse populations in the tails of NGC 2623. It would be plausible that region EC falls on a local region of enhanced star formation, causing its diffuse light colors to be bluer than other regions of NGC 3256 E. However, region EC does not include any young star clusters, instead containing only one cluster whose colors suggest that it predates the merger. The rest of the regions we measured are gathered around $V - I \approx 0.7$ and $B - V \approx 0.8$ and are off the BC06 track. Regardless, these offset colors suggest faint population ages of about 800–1000 Myr. It is likely that most of these diffuse light regions do not have colors consistent with the BC06 track because of the low surface brightness of NGC 3256 E, resulting in large photometric errors. It is unlikely that Hα line emission could be responsible for the offset from the model, although this emission would move measurements in the observed direction relative to the models, because such recent star formation is usually quite bright and lumpy.

4. DISCUSSION

4.1. Comparing Cluster Ages with Tail Ages

The age of the tidal tails, which we define as $\tau_{tail}$, refers to the time since perigalacticon of the two progenitor galaxies, because they form from material ejected after the galaxies undergo their closest approach. The ages of tails can be estimated from simulations and are probably accurate to within ∼20% (∼30–100 Myr; Barnes & Hibbard 2009). In this section, we briefly summarize previous simulations of our sample of mergers, and we compare tail ages from those simulations with our measured cluster ages.

We find that, for most systems, there is a period of increased cluster formation near the time that the tidal tails formed. We quantify the time of this cluster formation (hereafter denoted $\tau_{clus}$) by comparing the density peak of the color distribution with cluster evolution model predictions. These density plots are shown in the right panels of Figure 15. Contours are plotted, and the density peak is marked with a circle. The colors of the peak are then compared with a BC06 track to obtain an age (shown in left panels of Figure 15).

4.1.1. NGC 520

The interaction history of NGC 520 is the least well understood of our sample. Stanford & Balcells (1991) ran the most recent simulation of the system, comparing to infrared and optical images, as well the H I velocity field. Their best match to these observations is at a simulated age of ∼300 Myr ago. The system is particularly complicated, however, because Stanford & Balcells find that their simulations were not fully consistent with two colliding disk galaxies, due to the presence of a third dwarf galaxy, UGC 957. They conclude that the southern tail formed from the interaction of two massive disk galaxies and that the northern tail is the result of a passage by UGC 957. If the two tails formed via different interactions, we might expect differences in their cluster ages. Despite these complexities, we adopt a best guess of $\tau_{tail} \sim 300$ Myr.

The northern tail of NGC 520 contains only three young clusters, making a color density plot impractical here. However, the three clusters are tightly grouped around 100 Myr on the BC06 track; we therefore approximate their ages to be $\tau_{clus} \sim 100$ Myr. The majority of the south tail clusters appear to be older, and, based on their color distribution in Figure 15, they are consistent with a period of cluster formation that began around $\tau_{clus} \sim 260$ Myr ago.

The differences in the numbers and ages of the clusters detected in the north and south tails appear to be consistent with the scenario put forth by Stanford & Balcells. The passage of a dwarf galaxy would not necessarily result in a starburst as intense as one resulting from two equal-mass galaxies, because the dwarf galaxy would strip less gas to form clusters. We detect many more clusters in the southern tail, which Stanford & Balcells predict is the result of a disk–disk interaction, than the northern tail, which likely formed from the passage of the dwarf galaxy UGC 957. Stanford & Balcells speculate that the
A dwarf galaxy might have formed the northern tail as the disks were interacting, around the same time the southern tail was forming. However, the tight age grouping of the three clusters in NGC 520 N seems to indicate that cluster formation took place earlier than in NGC 520 S.

**Figure 13.** $B - I$ images of NGC 520 (top left), NGC 2623 (top right), and NGC 3256 (bottom left). The scale on bottom gives the $B - I$ color values.

**Figure 14.** Diffuse light colors for all three galaxies. Regions indicated in the legend correspond to Figure 13. Asterisks mark the median color of clusters found in that tidal tail that presumably predate the merger. Asterisks inside squares indicate that there were very few clusters that predate the merger ($\leq 3$). The solid black line is a BC06 cluster evolution track.

### Table 5

| Galaxy      | Region | $(V - I)_{\text{diffuse}}$ | $(B - V)_{\text{diffuse}}$ |
|-------------|--------|-----------------------------|-----------------------------|
| NGC 520     | NA     | 1.13                        | 0.70                        |
|             | NB     | 1.05                        | 0.60                        |
|             | SA     | 1.14                        | 0.71                        |
|             | SB     | 0.94                        | 0.49                        |
|             | SC     | 0.90                        | 0.47                        |
|             | SD     | 0.88                        | 0.46                        |
|             | SE     | 0.97                        | 0.49                        |
| NGC 2623    | NA     | 0.96                        | 0.48                        |
|             | NB     | 1.07                        | 0.42                        |
|             | NC     | 0.76                        | 0.33                        |
|             | ND     | 0.90                        | 0.47                        |
|             | SA     | 0.88                        | 0.45                        |
|             | SB     | 0.87                        | 0.40                        |
|             | SC     | 0.92                        | 0.38                        |
|             | SD     | 0.91                        | 0.41                        |
|             | SE     | 0.96                        | 0.42                        |
|             | P      | 0.68                        | 0.31                        |
| NGC 3256    | EA     | 0.77                        | 0.82                        |
|             | EB     | 0.71                        | 0.79                        |
|             | EC     | 0.78                        | 0.39                        |
|             | ED     | 0.83                        | 0.76                        |
|             | EE     | 0.66                        | 0.63                        |
4.1.2. NGC 2623

Privon et al. (2013) simulated NGC 2623 and estimated that an age \( \tau_{\text{tail}} = 220 \pm 30 \) Myr best reproduces spatial and kinematic distributions of \( \text{H}_2 \). Privon et al. also successfully recreated the pie wedge region, showing that it is probably material from the northern tail that has fallen back through the main body and is currently on a southward trajectory.

We measure clusters in NGC 2623 N to have a peak density in color corresponding to an age of \( \tau_{\text{clus}} \sim 230 \) Myr; this supports the scenario that cluster formation began at the same time that the tail formed. There are some clusters that appear to be older than the tail, however, as we discussed in Section 3.3.1; we believe this is due to photometric scatter resulting from low S/N. NGC 2623 S possesses too few clusters to reliably measure \( \tau_{\text{clus}} \), although it is clear from Figure 9 that most of the clusters are slightly bluer than the color associated with the tail age. It is possible that formation of clusters in the south tail was somewhat delayed relative to the tail itself, but uncertainties in tail and cluster ages are too large to definitively establish such a delay.

Inspection of Figures 9 and 15 shows that clusters in the pie wedge have a very narrow range of colors, suggesting that they all formed at approximately the same time; we measure \( \tau_{\text{clus}} \) to be \( \sim 100 \) Myr. These clusters are clearly bluer and hence younger than clusters in the tails of NGC 2623. This result is consistent with the scenario proposed by Evans et al. (2008), where the pie wedge formed from debris from the inner region of the northern tail. They suggest that the debris fell back through the main body, inducing a burst of star formation (see also Privon et al. 2013). While Privon et al. do not provide an age for the pie wedge, their Figure 8 shows snapshots of the merger at different times. At 85 Myr ago, the debris can be seen falling southward, past the main body, roughly consistent with our cluster formation timescale.

4.1.3. NGC 3256

Recent unpublished results from simulations place NGC 3256 at \( \tau_{\text{tail}} = 450 \pm 50 \) Myr (G. Privon, private communication). The simulation is based on spatial and kinematic \( \text{H}_2 \) images of the system and was run using the same methodology as for NGC 2623.

Clusters in the eastern tail have the largest spread in color of any system in our sample, with a weak density peak, \( \tau_{\text{clus}} \sim 260 \) Myr. This suggests a longer duration of cluster formation in this tail. These ages are consistent with previous results. Tramche et al. (2007) obtained spectroscopic ages for three clusters in the western tail, and found two clusters with ages of \( \sim 80 \) Myr, and a third with an estimated age of \( \sim 230 \) Myr. The latter fits well within the range that we find for clusters in the eastern tail.

4.1.4. The Timescale of Cluster Formation

In the three systems studied here, we have found that cluster formation typically begins with the tidal tail formation, although in a few cases a delay cannot be ruled out. This
type of delay was also found by Bastian et al. (2005) in NGC 6872. We therefore conclude that, in general, $\tau_{\text{clus}} \lesssim \tau_{\text{tail}}$.

$\tau < 10$ Myr clusters have not formed in any of the tails studied here. We confirm this by examining HST H$\alpha$ images of the two most recent mergers, NGC 2623 and NGC 520, and find no H$\alpha$ emission in any of their tails. We speculate that either the tails have used up their gas, or, because the gas is not collisionless, most of the remaining gas was largely dispersed during the interaction. It is worth noting, however, that clusters with age $\tau < 10$ Myr have been reported in the tidal tails of the Tadpole galaxy and NGC 6872 (Tran et al. 2003; Bastian et al. 2005). In the case of NGC 6872, the time since tail formation is $\sim 145$ Myr (Horellou & Koribalski 2003), making NGC 6872 significantly younger than any interacting system in our sample (except for the pie wedge). It is possible that NGC 6872 has simply not yet dispersed its tidal tail gas, resulting in newly formed clusters.

Based on our cluster age distributions, we suggest the following scenario: initially, the progenitor galaxies form clusters at a lower, approximately constant rate. Once the two galaxies begin their interaction, many of these disk clusters, along with other disk material, are stripped and form the tidal tails. The stripped gas typically begins forming clusters immediately, resulting in an increased rate of cluster formation. The process continues in the tails at a lower rate until the gas reservoir is exhausted or the gas is dispersed.

### 4.2. Comparing Cluster Ages Across Galaxies

We suggest the following sequence of merger ages: NGC 2623 is the most recent of the three mergers, followed by NGC 520, with NGC 3256 being the oldest. This sequence is supported by both our estimated cluster ages and simulated ages of tidal tails (and thus ages of the mergers themselves). We note that the age sequence suggested by these simulations is different than what the Toomre Sequence suggests, as NGC 520 and NGC 2623 are flipped (Toomre 1977).

We find that clusters in the pie wedge have ages around $\tau_{\text{clus}} \sim 100$ Myr. The north tail of NGC 2623 contains clusters with ages at $\tau_{\text{clus}} \sim 230$ Myr, while the few south tail clusters are slightly younger, although we do not attempt to quantify their ages. NGC 520, the next youngest merger, exhibits a slight age difference among clusters in different tails. NGC 520 N has clusters with ages $\tau_{\text{clus}} \sim 100$ Myr, while NGC 520 S has clusters with $\tau_{\text{clus}} \sim 260$ Myr. The oldest merger, NGC 3256, contains clusters in the eastern tail with ages $\tau_{\text{clus}} \sim 260$ Myr, although we caution that the broad age distribution in NGC 3256 E suggests that cluster formation likely began earlier than 260 Myr ago. For a direct comparison, all the values of $\tau_{\text{tail}}$ and $\tau_{\text{clus}}$ are listed in Table 3.

#### 4.3. How are the Tidal Tail Age and Luminosity Function Related?

We have measured the LFs for all tails where possible, and find tentative evidence that younger mergers exhibit shallower LFs, although our sample size is small. MLI found that a LF with $-2.5 < \alpha < -2$ provided qualitatively acceptable fits to their statistically determined cluster sample in tails where the measurement was possible, although they were not able to directly fit the LF with a power law due to the poor quality of the data. Whitmore et al. (2014) measured the luminosity function in a variety of spiral galaxies in search of various correlations between $\alpha$ and galactic environment. A weak negative correlation was found between star formation rate (SFR) and $\alpha$ (i.e., galaxies with high SFR tend to have flatter LFs). For instance, the Antennae, a major merger with a relatively high SFR, had the second lowest $\alpha$ value in their sample, at $\alpha = -2.07 \pm 0.03$.

No measurements of the cluster LF were made in tidal tails, however. While $\alpha$ tends to decrease with the tail age, all $\alpha$ values in our sample are within the range observed in a wide variety of other environments (Whitmore et al. 2014 and references therein).

### 5. CONCLUSIONS

We have used ACS/WFC observations from HST to directly observe star clusters in the tidal tails of three nearby mergers. We draw the following conclusions.

1. Every tidal tail in our sample, as well as the pie wedge, contains a population of star clusters. We note that NGC 520 N and NGC 3256 E were reported to have no statistically significant cluster presence in M11.

2. We estimated the ages of clusters in each tidal tail and compared with estimated ages for the tails themselves from simulations. The tidal tails in NGC 2623 contain a population of clusters which appear to have formed during the formation of the tails. Tails of NGC 520 and NGC 3256 possess several clusters that appear to predate the merger, in addition to a population of clusters that formed at, or soon after, the formation of the tails.

3. In every tidal tail in our sample, cluster formation lasted for several tens of millions of years, but no very recent formation (in the last few million years) has occurred in any of the tails.

4. Simulations place the formation of tails in the following sequence, from youngest to oldest: the pie wedge, NGC 2623, NGC 520, NGC 3256. Ages obtained from clusters generally agree with this sequence.

5. The diffuse light in the tails of NGC 520 and NGC 2623 exhibits a gradient in color across the tail (as opposed to along it), which is likely indicative of systematic patterns in the ages of the diffuse stellar population. To our knowledge, such color gradients in the diffuse stellar light in tidal tails of these galaxies have not been previously reported. The gradient is loosely traced by the spatial distribution of young and old star clusters within the tail. We interpret this gradient as a superposition of broadly distributed older stellar material and younger stars and clusters that formed along the center of the tail, where gas is densest.

6. The LFs of clusters in our tidal tail sample are similar to those found in a variety of galactic environments. We tentatively find that as the merger age increases, the luminosity function tends to become steeper.

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