Massive Star Cluster Formation and Destruction in Luminous Infrared Galaxies in GOALS. II. An ACS/WFC3 Survey of Nearby LIRGs

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Abstract

We present the results of a Hubble Space Telescope WFC3 near-UV and Advanced Camera for Surveys Wide Field Channel optical study into the star cluster populations of a sample of 10 luminous infrared galaxies (LIRGs) in the Great Observatories All-Sky LIRG Survey. Through integrated broadband photometry we have derived ages, masses, and extinctions for a total of 1027 star clusters in galaxies with \( d_L < 110 \) Mpc in order to avoid issues related to cluster bending. The measured cluster age distribution slope of \( d\mathcal{N}/d\tau \propto \tau^{-0.5+0.06-0.12} \) is steeper than what has been observed in lower-luminosity star-forming galaxies. Further, differences in the slope of the observed cluster age distribution between inner- (\( d\mathcal{N}/d\tau \propto \tau^{-1.07+0.12} \)) and outer-disk (\( d\mathcal{N}/d\tau \propto \tau^{-0.37+0.09} \)) star clusters provide evidence of mass-dependent cluster destruction in the central regions of LIRGs driven primarily by the combined effect of strong tidal shocks and encounters with massive giant molecular clouds. Excluding the nuclear ring surrounding the Seyfert 1 nucleus in NGC 7469, the derived cluster mass function (CMF; \( d\mathcal{N}/dM \propto M^{\alpha} \)) offers marginal evidence for a truncation in the power law at \( M_\ast \sim 2 \times 10^6 M_\odot \) for our three most cluster-rich sources, which are all classified as early stage mergers. Finally, we find evidence of a flattening of the CMF slope of \( d\mathcal{N}/dM \propto M^{-1.42\pm0.1} \) for clusters in late-stage mergers relative to early stage (\( \alpha = -1.65 \pm 0.02 \)), which we attribute to an increase in the number of massive clusters over the course of the interaction.

Unified Astronomy Thamesaurus concepts: Young star clusters (1833); Starburst galaxies (1570); Infrared galaxies (790); Interstellar medium (847); Star formation (1569)

Supporting material: machine-readable tables

1. Introduction

Imaging surveys of high-redshift star-forming galaxies reveal that these systems tend to display turbulent disks, which host star-forming clumps with stellar masses of \( \sim 10^{7-8} M_\odot \), and sizes of 0.5–5 kpc (Elmegreen et al. 2004, 2009; Daddi et al. 2010; Livermore et al. 2015). These extreme clumps are \( \sim 100 \times \) more massive than the typical giant molecular clouds (GMCs) observed in the Local Universe, and give rise to super star clusters (SSCs) with masses which can reach \( \geq 10^6 M_\odot \); i.e., similar to the most massive known globular clusters and 1–2 orders of magnitude more massive than any young cluster or H II region found in nearby normal galaxies like the Milky Way (MW) or M51 (Kobulnicky & Johnson 1999; Whitmore et al. 2014; Cook et al. 2016; Dessauges-Zavadsky & Adamo 2018).

While the total number of massive clusters formed is largely set by the gas density in the interstellar medium (ISM), high-resolution simulations of cluster formation show that strong stellar (internal) feedback not only changes the efficiency of cluster formation within GMCs, but also alters the dynamical state of the cluster and in some cases may rapidly disrupt the cloud altogether (e.g., Li et al. 2017; Grudić et al. 2021). Star clusters may also lose mass via interaction (external) with their galactic environment (e.g., Lamer et al. 2005; Gieles et al. 2006), resulting in low disruption rates in low pressure environments and high disruption rates in intensely star-forming regions of the ISM. From a theoretical perspective, after their formation clusters lose mass in three phases: (1) stellar evolution and feedback, (2) two-body relaxation-driven evaporation in their host galaxy’s tidal field, and (3) tidal shocks resulting primarily from collisions with GMCs and passages of spiral arms (see Krause et al. 2020). During the first phase, expulsion of natal gas by stellar winds and supernovae perturbs the clusters’ potential and leaves up to 90% unbound or destroyed (Lada & Lada 2003). The latter stages of cluster evolution depend both on the clusters’ location within the galaxy, and its overall density.

However, there is no consensus for what the relative importance of both internal feedback and the external galactic environment (mass-dependent cluster disruption) have on altering the universality of star cluster properties (see: Portegies Zwart et al. 2010; Whitmore et al. 2010; Bastian et al. 2012; Fall & Chandar 2012; Fouesneau et al. 2012; Chandar et al. 2015;
Johnson et al. 2017). Observationally, the shape of both the cluster luminosity function (CLF) and cluster mass function (CMF) as well as the star cluster age distribution have been found to vary between quiescent and starburst galaxies in the Local Universe (Gieles 2009; Bastian et al. 2012; Krumholz et al. 2019; Adamo et al. 2020). While Fall et al. (2005) and Whitmore et al. (2007) interpret the age distribution for star clusters in the Antennae galaxies (NGC 4038/39), the nearest example of a massive galaxy merger, as evidence for mass independent cluster disruption (e.g., feedback-driven rapid gas dispersal) up to \( \sim 10^5 \, M_\odot \), Lamers et al. (2005) and Silva-Villa et al. (2014) have suggested that strongly varying tidal fields and collisions between GMCs of high surface density can be the dominant physical mechanism which disrupts clusters in such extreme environments. Indeed, simulations of equal-mass galaxy mergers (Kruijssen et al. 2011) find that 80\%–85\% of the cluster disruption seen may be accounted for by tidal shocks.

Luminous and ultra-luminous infrared galaxies (LIRGs; defined as having IR luminosities \( L_{\text{IR}} \approx 10^{11} \, L_\odot \); ULIRGs: \( L_{\text{IR}} > 10^{12} \, L_\odot \)) host the most extreme stellar nurseries in the Local Universe, with star-forming clump masses and radii similar to high-redshift galaxies (Miralles-Caballero et al. 2011; Larson et al. 2020). The activity in LIRGs is largely interaction triggered, with the progenitors observed to be gas-rich disk galaxies involved in minor interactions (at the low-luminosity end) or major merger events (Stierwalt et al. 2013). This framework is supported by simulations of gas-rich mergers, which show the inward flow of star-forming gas via tidal and bar-driven dissipation to a nuclear starburst, and the eventual settling into early-type galaxies (Barnes & Hernquist 1992; Barnes 2004; Hopkins et al. 2006). Further, these simulations demonstrate that the chaotic environment of the nuclear region is contrasted against the outer regions of a galaxy merger, where increases in the dense gas and star formation efficiency are comparatively mild (Moreno et al. 2021). Since local LIRGs can be studied at high resolution across the entirety of their disks, they are ideal laboratories for testing location-dependent cluster formation and disruption in extreme merger-driven environments.

To better understand cluster formation and evolution in LIRGs, we previously combined our Hubble Space Telescope (HST) F435W (B) and F814W (I) Advanced Camera for Surveys Wide Field Channel (ACS/WFC) data with far-UV ACS/Solar Blind Channel (SBC) F140LP (FUV) data to age-date \( \sim 400 \) clusters in a combined sample of 22 LIRGs as part of the Great Observatories All-Sky LIRG Survey (GOALS; Armus et al. 2009; Linden et al. 2017). Overall we found evidence of a steeper decline in the number of clusters per unit time as a function of increasing cluster age (\( d N / d \tau \propto \tau^{-0.9} \) for \( 3 < \tau < 300 \, \text{Myr} \)) relative to normal galaxies, which is a further indication that clusters in massive mergers suffer destruction at a much more rapid rate than normal star-forming galaxies.

However, our 2017 study was limited by three issues: (i) the small field of view (FOV) of the SBC observations \( (30'' \times 30'') \) often limited us to clusters in the central regions of the galaxies in our sample; (ii) the completeness-corrected cluster sample contained only the most massive clusters \( (M \geq 10^4 \, M_\odot) \) in each galaxy due to the FUV sensitivity achieved; and (iii) age–extinction degeneracies were present for clusters within particular color ranges. Here, we present HST WFC3 U-/F336W band observations of all 10 \( L_{\text{IR}} > 10^{11.4} \, L_\odot \) U/LIRGs in GOALS scheduled to be observed by the James Webb Space Telescope (JWST) as part of the ERS program “A JWST Study of the Starburst-AGN Connection in Merging LIRGs” (PID 1328—PI Armus) and GTO campaigns. The combination of broad- and narrow-band near-infrared (NIR) and mid-infrared (MIR) imaging with JWST at comparable resolution as HST will allow us to identify all of the very youngest (\( \sim 1 \, \text{Myr} \)) and most highly embedded SSCs in LIRGs. These sources are often missed in UV-optical studies of cluster formation in nearby galaxies, but are crucial for a complete picture of stellar feedback in the ISM.

Crucially, our new WFC3/UVIS observations provide vast improvements in sensitivity over prior HST detectors operating at 0.3 \( \mu \text{m} \), and combined with our existing HST data (ACS/WFC F435W and F814W data), provide high-resolution maps of the distribution of star clusters over the entire extent of each LIRG. Further, the F336W filter provides a much improved lever arm for age-dating clusters relative to the F140LP filter, which allows us to break the reddening–age degeneracy and thus more accurately measure (to within 0.1–0.2 dex in \( \log (\tau) \)) cluster ages and cluster masses. A fundamental goal of the present paper is to investigate what role the host galaxy environment, and localized ISM conditions within individual LIRGs, play in the rapid destruction of SSCs observed in LIRGs.

The paper is organized as follows: In Section 2, the observations, data reduction, and sample selection are described. Our method for identifying clusters and determining cluster ages, masses, and extinctions is described in Section 3. In Section 4, we discuss the completeness limits of our cluster sample. In Section 5, the age and mass functions are discussed within the context of lower-luminosity star-forming galaxies and clusters found in both the inner and outer disks of our galaxy sample. Finally, we discuss our results in terms of the merger stages (MSs) of each system. Section 6 is a summary of the results.

Throughout this paper, we adopt a Wilkinson Microwave Anisotropy Probe Cosmology of \( H_0 = 69.3 \, \text{km s}^{-1} \, \text{Mpc}^{-1} \), \( \Omega_{\text{matter}} = 0.286 \), and \( \Omega_{\Lambda} = 0.714 \) (e.g., see Hinshaw et al. 2013).

2. Observations and Sample Selection

The F336W images of 10 LIRG systems were obtained from 2018 August–November (PI: A. Evans; PID 15472). Table 1 is a summary of the general properties of the sample. Each galaxy was observed with four dithered exposures in ACCUM mode, and when possible, placed at the center of the UVIS2 chip, due to the increased sensitivity at UV wavelengths relative to UVIS1. The approximate integration times for each galaxy is 41 minutes. The data were reduced with the Multidrizzle software provided by STScI to identify and reject cosmic rays and bad pixels, remove geometric distortion, and finally, combine the resulting mosaics with our existing ACS/WFC F435W and F814W observations (see Figure 1). The final pixel scale of our WFC3 images is \( 0''/0396 \) pix\(^{-1}\). The ACS/WFC and WFC3/UVIS cameras have comparable fields of view \( (202'' \times 202'' \) and \( 162'' \times 162'' \), respectively), and cover sufficient area to enable single-pointing observations of these U/LIRGs. Figures 13–21 show the three-panel mosaics for the remaining nine galaxies. To understand the impact of combining results from galaxies that span a factor of \( \sim 3 \) in distance, we performed simulations of cluster blending: by progressively smoothing HST WFC3 archival imaging of the Antennae Galaxies \( (D_L = 22 \, \text{Mpc} ) \).
Whitmore et al. (2010), reidentifying star clusters, and recomputing the luminosity function, we determined that blending begins to hamper our ability to accurately measure cluster properties (age, mass, extinctions), and thus determine the true slope, $\alpha$, of the underlying CMF, at smoothing lengths of $\geq 5$ pixels (i.e., $\Delta \alpha > 0.3$). This test demonstrates that clusters can be individually detected and their physical properties can be accurately recovered in galaxies out to a distance of $\sim 100$ Mpc. Therefore we limit our primary cluster analysis in this paper to the five nearest systems that have have $D_L \leq 100$ Mpc, such that we can be confident our results are not biased toward large, unresolved, complexes of multiple star clusters. However, we run the same cluster identification and photometric analysis on all 10 LIRG systems. We provide the derived physical quantities and photometry which appear in Tables 2 and 3, respectively.

### 3. Cluster Identification and Model Fitting

#### 3.1. Cluster Identification

Star clusters in all three bands were selected using the program Source Extractor (Bertin & Arnouts 1996). The identification of clusters and the extraction of photometry is performed after a diffuse background subtraction is applied to each image. This subtraction is described in detail in Linden et al. (2017), and is designed to remove starlight that is unassociated with the compact sources identified in each galaxy. Cluster photometry across all background-subtracted images was then calculated using the IDL package APER. We used an aperture of radius 3.0 pixels, with an annulus from 4–5 pixels to measure the local background surrounding each cluster. Aperture corrections for ACS/WFC and WFC3 were calculated based on the encircled energy values presented in

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### Table 1

| Galaxy      | R.A.         | Decl.        | $D_L$ (Mpc) | MS | Log(LIR) | Log($M_*$) | SFR ($M_\odot$ yr$^{-1}$) | MIR Size (kpc) | $b/a$ (deg) | PA (deg) |
|-------------|--------------|--------------|-------------|----|----------|-----------|----------------------------|----------------|------------|----------|
| IC 1623     | 01$^h$07$^m$47$^s$.180 | $-17^\circ$30$'^{\prime}$25$''$.30 | 84.40 | 3 | 11.71 | 11.21 | 94.09 | 4.60 | 0.92 | 302.7 |
| IRAS F08572+3915 | 09$^h$00$^m$25$^s$.390 | $+39^\circ$03$'^{\prime}$54$''$.40 | 261.13 | 3 | 12.16 | 11.81 | 254.32 | 4.70 | 0.31 | 10.8 |
| NGC 3256    | 10$^h$27$^m$51$^s$.270 | $-43^\circ$54$'^{\prime}$13$''$.49 | 45.66 | 3 | 11.64 | 11.06 | 76.46 | 2.10 | 0.83 | 25.0 |
| IRAS F12112+0305 | 12$^h$13$^m$46$^s$.000 | $+02^\circ$48$'^{\prime}$38$''$.0 | 329.38 | 3 | 12.36 | 11.34 | 402.89 | 9.83 | 0.64 | 9.3 |
| Mrk 231$^a$ | 12$^h$56$^m$14$^s$.234 | $+56^\circ$52$'^{\prime}$25$''$.24 | 188.57 | 6 | 12.50 | 10.98 | 380.19 | 3.34 | 0.83 | 25.0 |
| IRAS 14378-3651 | 14$^h$40$^m$59$^s$.008 | $-37^\circ$04$'^{\prime}$31$''$.94 | 302.13 | 6 | 12.23 | 11.94 | 79.9$^b$ | 5.78 | 0.67 | 41.7 |
| Arp 220     | 15$^h$34$^m$57$^s$.255 | $+23^\circ$30$'^{\prime}$11$''$.30 | 81.93 | 5 | 12.28 | 11.06 | 327.74 | 1.53 | 0.87 | 286.2 |
| NGC 6240    | 16$^h$52$^m$58$^s$.871 | $+02^\circ$24$'^{\prime}$03$''$.33 | 108.67 | 4 | 11.93 | 11.59 | 148.44 | 2.26 | 0.45 | 279.6 |
| IRAS F17207-0014 | 17$^h$23$^m$21$^s$.955 | $-00^\circ$17$'^{\prime}$00$''$.94 | 189.03 | 5 | 12.46 | 11.18 | 501.22 | 3.75 | 0.80 | 30.7 |
| NGC 7469    | 23$^h$03$^m$15$^s$.623 | $+08^\circ$52$'^{\prime}$26$''$.39 | 66.68 | 2 | 11.65 | 11.38 | 80.26 | 1.37 | 0.53 | 56.3 |

Notes. Infrared luminosity and stellar mass are given in units of $L_{\odot}$ and $M_{\odot}$, respectively. R.A., decl., distance, infrared luminosity, stellar mass, and star formation rate (SFR) are taken from Howell et al. (2010). MSs are taken from Haan et al. (2013); Kim et al. (2013), and Stierwalt et al. (2013). MIR sizes are taken from Díaz-Santos et al. (2010). The values marked with an asterisk (*) denote a galaxy whose central region is unresolved in the Spitzer 2D IRS Spectra. The $b/a$ and PA are taken from Kim et al. (2013).

$^a$ Data for Mrk 231 is taken from Sanders et al. (2012).

$^b$ An estimate for the SFR of IRAS 14378-3651 is taken from Sturm et al. (2011).
We additionally applied a correction for foreground Galactic extinction, using the Schlafly & Finkbeiner (2011) dust model combined with the empirical reddening law of Fitzpatrick (1999) available through the NASA Extragalactic Database.

In the process of doing photometry, we also removed sources with a signal-to-noise ratio S/N < 3 and which are not detected in all three filters. In total we extracted photometry for 2167 cluster candidates identified in the five nearest LIRGs. The number of detections \( N_{\text{det}} \) for each source are given in Table 4. We then used ISHAPE (Larsen 1999) to measure the 2D FWHM for all remaining sources by deconvolving the HST instrumental point-spread function with a King profile (King 1966). We find that a cut of 3 pixels FWHM (corresponding to an average cluster size of \( R_{\text{eff}} \sim 22 \) pc) effectively removes extended sources in both the nearest and farthest galaxies in the sample. This value is consistent with the upper-end of sizes observed for open star

| ID   | R.A.        | Decl.         | \( t_{c} \) | \( \sigma_{t_{c}} \) | \( M_{c} \) | \( \sigma_{M_{c}} \) | \( A_{V} \) | \( \sigma_{A_{V}} \) |
|------|-------------|---------------|-------------|------------------|-------------|------------------|------------|------------------|
| 1    | 233.74669054 | 23.480581701C | 8.73        | 0.13             | 9.02        | 0.05             | 4.50       | 0.22             |
| 2    | 233.72954053 | 23.475817413C | 8.02        | 0.38             | 7.07        | 0.19             | 0.80       | 0.31             |
| 3    | 233.748437605| 23.482745482C | 9.00        | 0.42             | 6.49        | 0.11             | 0.90       | 0.65             |
| 4    | 233.751644007| 23.484386024C | 8.26        | 0.09             | 6.65        | 0.05             | 0.60       | 0.13             |
| 5    | 233.764694288| 23.492547085C | 8.73        | 0.15             | 7.83        | 0.05             | 3.40       | 0.24             |
| 6    | 233.728218353| 23.482656154C | 6.48        | 0.35             | 5.16        | 0.11             | 3.00       | 1.02             |
| 7    | 233.732302621| 23.484575842C | 6.97        | 0.02             | 5.32        | 0.05             | 2.10       | 0.10             |
| 8    | 233.731859917| 23.486152064C | 8.26        | 0.27             | 5.49        | 0.14             | 0.80       | 0.23             |
| 9    | 233.725012898| 23.486914452C | 6.73        | 0.12             | 7.92        | 0.05             | 3.60       | 0.21             |
| 10   | 233.728399990| 23.488682409C | 6.97        | 0.07             | 4.05        | 0.00             | 0.80       | 0.23             |

**Table 2**

Derived Properties of Individual Star Clusters

**Table 3**

Observational Properties of Individual Star Clusters

**Table 4**

Cluster Detection Statistics and Overall Properties

| Galaxy | \( N_{\text{det}} \) | \( N_{c} \) | \( m_{U,\text{Out}} \) | \( m_{U,\text{Inner}} \) | \( t_{c} \) | \( \sigma_{t_{c}} \) | \( M_{c} \) | \( \sigma_{M_{c}} \) | \( A_{V} \) | \( \sigma_{A_{V}} \) |
|--------|----------------------|-------------|-------------------|-------------------|-------------|------------------|-------------|------------------|------------|------------------|
| Arp 220| 108                  | 46          | 24.19             | 23.28             | 8.33        | 0.53             | 5.94        | 0.91             | 0.7        | 0.48             |
| IC 1623 | 453                  | 180         | 24.85             | 23.84             | 6.97        | 0.53             | 5.21        | 0.89             | 0.4        | 0.58             |
| NGC 3256 | 1082                 | 549         | 24.51             | 23.82             | 7.99        | 1.06             | 5.29        | 1.17             | 0.6        | 0.75             |
| NGC 6240 | 141                  | 87          | 24.95             | 23.36             | 8.24        | 0.66             | 5.71        | 1.16             | 0.5        | 0.59             |
| NGC 7469 | 383                  | 165         | 24.41             | 23.71             | 7.24        | 0.79             | 4.82        | 0.95             | 0.4        | 0.55             |

**Note.** All values for age, mass, and extinction are given in \( \log(t/\text{yr}) \), \( \log(M/M_{\odot}) \), and magnitudes, respectively. (This table is available in its entirety in machine-readable form.)

**Table 5**

Cluster Detection Statistics and Overall Properties

| Galaxy | \( N_{\text{det}} \) | \( N_{c} \) | \( m_{U,\text{Out}} \) | \( m_{U,\text{Inner}} \) | \( t_{c} \) | \( \sigma_{t_{c}} \) | \( M_{c} \) | \( \sigma_{M_{c}} \) | \( A_{V} \) | \( \sigma_{A_{V}} \) |
|--------|----------------------|-------------|-------------------|-------------------|-------------|------------------|-------------|------------------|------------|------------------|
| Arp 220| 108                  | 46          | 24.19             | 23.28             | 8.33        | 0.53             | 5.94        | 0.91             | 0.7        | 0.48             |
| IC 1623 | 453                  | 180         | 24.85             | 23.84             | 6.97        | 0.53             | 5.21        | 0.89             | 0.4        | 0.58             |
| NGC 3256 | 1082                 | 549         | 24.51             | 23.82             | 7.99        | 1.06             | 5.29        | 1.17             | 0.6        | 0.75             |
| NGC 6240 | 141                  | 87          | 24.95             | 23.36             | 8.24        | 0.66             | 5.71        | 1.16             | 0.5        | 0.59             |
| NGC 7469 | 383                  | 165         | 24.41             | 23.71             | 7.24        | 0.79             | 4.82        | 0.95             | 0.4        | 0.55             |

**Note.** All flux values and 1σ uncertainties are given in erg s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\). (This table is available in its entirety in machine-readable form.)

Sirianni et al. (2005) and Deustua et al. (2016), respectively. We additionally applied a correction for foreground Galactic extinction, using the Schlafly & Finkbeiner (2011) dust model combined with the empirical reddening law of Fitzpatrick (1999) available through the NASA Extragalactic Database.

In the process of doing photometry, we also removed sources with a signal-to-noise ratio S/N < 3 and which are not detected in all three filters. In total we extracted photometry for 2167 cluster candidates identified in the five nearest LIRGs. The number of detections \( N_{\text{det}} \) for each source are given in Table 4. We then used ISHAPE (Larsen 1999) to measure the 2D FWHM for all remaining sources by deconvolving the HST instrumental point-spread function with a King profile (King 1966). We find that a cut of 3 pixels FWHM (corresponding to an average cluster size of \( R_{\text{eff}} \sim 22 \) pc) effectively removes extended sources in both the nearest and farthest galaxies in the sample. This value is consistent with the upper-end of sizes observed for open star clusters.
clusters in the MW, as well as simulations of star cluster formation in dwarf starburst galaxies (Lahén et al. 2020). In Figure 2 we show a zoom-in for three regions in IC 1623 with our cluster detections overlaid in blue squares. These regions highlight the structure and variable levels of background emission which surround these clusters. A total of 1027 confirmed clusters across the five nearest LIRGs meet the above criteria. We observe a large range of cluster magnitudes ($M_U = -7 \sim -17$ mag), with a median of $M_U = -10$ mag, where the brightest clusters are detected in both the central region and outer disks of these systems. The number of confirmed clusters for each source are given in Table 4.

Finally, in order to make detailed comparisons of clusters at different radii we adopt a similar methodology to Linden et al. (2019), to compute the deprojected galactocentric radius of each cluster ($r_G$) using the axis ratio ($b/a$) and position angle (PA) of the host galaxy (Jarrett et al. 2000; Paturel et al. 2003; Kim et al. 2013). The 13.2 $\mu$m mid-infrared size derived from Spitzer/IRS spectra serves as our best estimate (or upper limit) for the size of the central starburst, limited by the resolution of the Spitzer/IRS beam, within each galaxy (Díaz-Santos et al. 2010). By comparing the measured $r_G$ values to the 13.2 $\mu$m FWHM determined from a Gaussian fit to the 2D spectra, we can place clusters into two categories: those that fall within the MIR size of the galaxy (inner-disk clusters) and those that fall outside of the MIR size (outer-disk clusters). This separation allows us to test whether the cluster properties that we measure with HST are dependent on the current size of the starburst responsible for producing the bulk of the far-infrared emission.

We note that for several galaxies the MIR size is unresolved (FWHM is within 10% of that of the unresolved stellar PSF). Therefore while the 13.2 $\mu$m MIR size may not represent the true size of the compact starburst in each galaxy, it still serves as our best estimate for where the bulk of the SF activity responsible for heating the dust in each galaxy is. We also stress that for NGC 3256 and IC 1623 (the two galaxies we ultimately examine—see Section 5.1.1) the MIR sizes are resolved. In fact for high-resolution ground-based 5–15 $\mu$m imaging of VV 114 reveal that up to ~60% of the MIR emission is extended on kiloparsec scales (Le Floc’h et al. 2002). The values for the $b/a$, PA, and MIR size (FWHM) of each system are given in Table 1.

3.2. Model Fitting

For all confirmed clusters, the measured three-band fluxes were compared against a library of simple stellar population (SSP) evolutionary models that were computed using the isochrone synthesis code Starburst99 (Leitherer et al. 1999), hereafter referred to as SB99. This code computes the evolution of an instantaneous burst based on a Kroupa IMF and the stellar evolution models over an age range of 1 Myr–10 Gyr (e.g., Bertelli et al. 1994). Crucially we add the contribution from nebular emission lines which may contribute up to 40% of the emission observed in the broadband F814W filter for clusters with ages ~3–5 Myr (Reines et al. 2010; Zackrisson et al. 2011). We also choose to adopt a solar metallicity, as suggested for LIRGs by Kewley et al. (2010), and the starburst attenuation curve of Calzetti et al. (2000). The total attenuation of the stellar continuum, $R_V = A(V)/E(B-V) = 4.05 \pm 0.8$, is calibrated specifically for starburst galaxies and differs from the typical MW value of $R_V \sim 3.1$ (Calzetti et al. 2000). It has been shown empirically that clusters and H II regions are more heavily attenuated than the underlying stellar continuum, due to the fact that these objects are often found near dusty regions of ongoing
star formation (Calzetti et al. 1994). Our model choices allow us to make consistent comparisons with results from the Legacy Extragalactic UV Survey (LEGUS), which adopt the Yggdrasil nebular+continuum models Zackrisson et al. (2011) to determine cluster ages, masses, and extinctions (e.g., Adamo et al. 2017; Ryon et al. 2017; Cook et al. 2019).

We construct grids for the age, mass, and extinction model parameters and perform a $\chi^2$ fit for each point in the grid. We use these to obtain the marginalized posterior distribution function for all derived parameters, and represent the error in our model fit as the FWHM of each distribution. In Figure 3 we give an example of our model-fitting routine for one cluster in NGC 3256, chosen to demonstrate our ability to accurately recover the properties of a young, moderately extincted ($A_V = 1.7$), massive ($10^4 M_\odot$) cluster. We show both the maximum a posteriori probability (blue line) as well as the median (pink line) of each parameter along with the corresponding 1$\sigma$ errors. This cluster represents a prototypical degenerate case from our previous F140LP observations, and with the substitution of the F336W filter we are able to recover cluster age, mass, and extinction to within 0.2 dex. As described above, this is crucial for accurately recovering the underlying slope of the age and mass distribution functions for each galaxy. The median age, mass, and extinction along with median absolute deviation of each distribution are given in Table 4.
4. Completeness and the Mass–Age Diagram

4.1. Completeness

In order to determine the completeness limit of our cluster sample, we follow a similar prescription to Messa et al. (2018), which utilizes the LEGUS Cluster Completeness Tool. We first create a set of synthetic clusters with the BAOlab software (Larsen 1999) by convolving the WFC3 F336W PSF with a King profile specified with effective radii of 1, 5, and 10 pc. The resulting sources are then distributed within our science targets in two ways: (1) 100 clusters with apparent magnitudes of $18 < m_U < 26$ are randomly placed within the central 300 pixels, which is chosen to match the median MIR size in our five sample galaxies, of each F336W science frame, and (2) 500 clusters are randomly placed outside the central 300 pixels of each science frame. In this way we can directly account for significant variations in the depth of our $U$-band images in the central regions of the LIRGs in our sample. The same procedure described in Section 3 is then applied to these images and the fraction of simulated clusters recovered in the final catalog is calculated for each effective radius as a function of input cluster magnitude.

For the five LIRGs in our cluster sample the total 90% completeness limits for the inner and outer regions are given in Table 4. It is clear that in the central regions we are ~1 magnitude less sensitive, and that we achieve consistent depth ($m_{U,\text{inner,90\%}}$) in F336W across the five galaxies in our sample given that the range in magnitudes is relatively small. The cluster-weighted median completeness limit for the inner and outer regions of our LIRG sample are $M_U = -9.3$ and $-8.4$, respectively, and are shown as dotted and solid lines in Figure 4.

4.2. The Mass–Age Diagram

In Figure 4 we plot the derived age and mass of each cluster identified in the sample with outer-disk clusters ($N_c = 809$) plotted in black and inner-disk clusters ($N_c = 218$) plotted in purple. The lack of low-mass ($< 10^4 M_\odot$) clusters with ages $\geq 100$ Myr is due to the fact that clusters dim as they age and eventually become fainter than our UV detection limits. By applying our inner-disk completeness limit to the SB99 model we can define regions of this mass-age parameter space where we are observationally complete in both the inner and outer disks of the LIRGs in our sample. Mass-limited cluster samples have the advantage over luminosity-
limited samples because they recover the underlying shape of the age and mass distributions, and are thus not affected by the distance to each galaxy (Renaud 2020).

The two cuts were selected to sample distinct regions of the mass and age distribution for which we could maintain completeness. We define Regime 1 to be

\[
5.2 < \log(M/M_\odot) < 8, \\
6.6 < \log(\tau) < 8.7.
\]

And Regime 2 to be

\[
4.5 < \log(M/M_\odot) < 8, \\
6.0 < \log(\tau) < 7.5.
\]

Regime 1 is chosen to match, as closely as possible, the age and mass limits from Fall et al. (2005) and Linden et al. (2017), allowing us to make accurate comparisons to the age distributions of clusters in other nearby galaxies, while also avoiding selecting the very youngest clusters, which may actually be unresolved unbound associations (Kruijssen & Bastian 2016). Regime 2 is chosen in order to measure the CMF of the young (\(\tau < 10^{-5}\)), recently formed clusters that best reflect the current conditions of the ISM in these systems (Adamo et al. 2020). When analyzing Regimes 1 and 2 we exclude the largest mass bin of \(\log(M/M_\odot) = 8.0\). These very high masses are most likely the result of either an imperfect extinction correction or multiple very compact star clusters in close proximity appearing as a single star cluster at the resolution of these images. We stress that the adopted FWHM cut helps minimize the inclusion of sources that are blends of \(\sim 2-3\) clusters. Finally, we note that while clusters of these masses are rare, Bastian et al. (2013) found several clusters in NGC 7252 with masses greater than \(10^7 M_\odot\), including one cluster with a total mass of \(\sim 10^8 M_\odot\). Finally, recent observations of a nearby (\(z = 0.0336\)) post-starburst galaxy have revealed massive clusters up to \(10^{10.5} M_\odot\) associated with a period of intense SF activity in the galaxy (Chandar et al.2021).

5. Discussion

After determining ages, masses, and extinctions for the entire cluster sample we directly compare these distributions with those of nearby normal and interacting galaxies. We focus on the interpretation of the derived cluster age distribution for both the individual systems and the sample as a whole as well as mass functions for combined samples of galaxies. Further, we will analyze the inner- and outer-cluster cluster distribution functions for each system. Ultimately, we discuss to what degree the differences observed in our cluster populations can be attributed to the extreme star-forming environment unique to LIRGs in the Local Universe.

5.1. Age Distribution

We consider the age distribution of clusters in our LIRG sample over Regime 1 described in Section 4. Specifically, we are interested in measuring the power-law index \(\gamma\), where \(dN/d\tau \propto \tau^\gamma\). In Figure 5 we show the differential number of clusters per time interval, \(\log(dN/d\tau)\), versus the median cluster age over that interval, \(\log(\tau)\) for all clusters in the mass range given in Equation (1). The plotted data are binned by 0.4 in \(\log(\tau)\) so as to fully encapsulate \(\sim 2\tau\) times the typical model errors of 0.2 in \(\log(\tau)\) discussed in Section 3. For clusters in the age range given in Equation (2) a weighted linear least-squares fit to the age distribution results a power-law index of \(\gamma = -0.54 \pm 0.12\). The slope of the cluster age distribution reflects a combination of any increase in the formation rate of clusters with \(10^{5.2} M_\odot < M_c < 10^8 M_\odot\) from \(10^{8.7}\) yr to the present day with any destruction of star clusters through the methods discussed above over the same age interval. In Section 5.1.2, we attempt to account for this ambiguity directly.

While the observed slope is slightly shallower than both the Antennae age distribution slope and the results from Linden et al. (2017), we see that our combined galaxy slope is consistent with the results for M83 and steeper than what is measured for lower-luminosity star-forming galaxies like the LMC. When examining the age distribution functions for our three most cluster-rich (i.e., \(N_c > 100\) SSCs) galaxies, we find that the slopes measured for IC 1623, NGC 3256, and the outer disk of NGC 7469 are all steep with \(\gamma = -0.4\) to 1 (Figures 6, 7, and 8, respectively).

We note that this analysis excludes the 19 clusters identified in the nuclear ring of NGC 7469. The star and cluster formation within nuclear rings is likely decoupled from the SFH of their host galaxies due to irregularities in the inflow rate of dense gas (Maoz et al. 2001). Indeed, \(\sim 30\%\) of the nuclear K-band light in NGC 7469 is due to a single source (Davies et al. 2004). Further, NGC 7469 is the only nearby galaxy in our sample that contains a bright Seyfert 1 nucleus, which may also affect the temperature and spatial distribution of the gas within the ring itself (Díaz-Santos et al. 2007). Therefore, we are unable to disentangle these effects from variations in the SFH, which ultimately complicates any comparison between the age distribution inferred for these clusters and the outer-disk clusters in this galaxy. In the following section we exclude this galaxy from the inner- and outer-disk comparison.
5.1.1. Inner- and Outer-disk Clusters

All three cluster-rich systems are classified as early stage mergers (Kim et al. 2013), suggesting that the similar dynamical state (e.g., tidal field) within the ISM of these galaxies may set the overall disruption rate seen. Existing wide-field WiFeS IFU observations of IC 1623 and NGC 3256 allow us to connect the cluster properties in both the inner and outer disks of these systems to the ionized gas. These two systems both exhibit strong evidence of galaxy-wide shock excitation induced by their ongoing merger activity (Rich et al. 2011). Multi-line Atacama Large Millimeter/submillimeter CO observations of GMCs in IC 1623 and NGC 3256 also suggest they are highly turbulent (Saito et al. 2015; Brunetti et al. 2021). With multi-line HCN/HCO+ observations Saito et al. (2018) further attributing this turbulence to galaxy-wide shocks in IC 1623.

By examining the age distribution functions for clusters identified as inner- or outer-disk clusters in NGC 3256 and IC 1623 a striking result emerges. The SSCs classified as inner disk ($N_c = 206$) show a distribution slope of $\gamma = -1.1 \pm 0.11$, whereas SSCs found in the outer disk ($N_c = 523$) have a distribution slope of $\gamma = -0.33 \pm 0.12$ (Figure 9). This inner-disk value is consistent with the results from Linden et al. (2017), where the FOV is well matched to the average MIR size. We stress that NGC 3256 and IC 1623 both individually show increases in the distribution slope between inner and outer-disk clusters, but the samples are combined here such that we achieve better statistics for each region. The outer-disk value is consistent with the results for M83 presented in Adamo & Bastian (2015), which is a prototypical spiral galaxy in the Local Universe, and suggests that differences in the observed slope between IC 1623 and M83 in Figure 6 are driven by the inner region of the galaxy.

It was shown by Gieles et al. (2006) that star clusters can be disrupted on $\sim$1–2 Gyr timescales by tidal shocks that arise from gravitational interactions with passing GMCs. However, the GMC volume density in the central regions of LIRGs is considerably higher than what is seen in other nearby galaxies.
It is likely that both internal feedback and external effects coexist for the youngest clusters. However, there’s a suggestion from simulations that the fraction of clusters which are destroyed by gas expulsion (i.e., *infant mortality*: Lada & Lada 2003) decreases in effectiveness with increasing ambient density of the star-forming region, while at the same time the disruptive effect of tidal shocks increases with ambient gas density (Pfeffer et al. 2018). It may be that infant mortality and the cruel cradle effect each dominate a different side of the gas density spectrum of star-forming regions. Their relative strength would then determine the relation between the cluster formation efficiency and the surface density of gas in galaxies (Kruisjes et al. 2012b; Johnson et al. 2017; Adamo et al. 2020).

Assuming spatially homogeneous distributions of clusters and GMCs, Gieles et al. (2006) found that clusters lose most of their mass in very close encounters with high relative velocities. The derived disruption timescale depends on the cluster mass ($M_c$), the half-mass–radius ($r_h$), and the product of the individual mean GMC surface density and the average local GMC density ($S \propto (\Sigma_{\text{GMC}}(M_c\cdot pc^{-3})\rho_{\text{GMC}}(M_c\cdot pc^{-3}))^{-1}$).

In Equation (5) we give the expression for the disruption timescale $t_{\text{dis}}$ for a cluster embedded in a strong external tidal field $S$ parameterized by the mass density and volume of the ISM in the solar neighborhood (Equation (24)—Gieles et al. 2006):

$$t_{\text{dis}} = 2.0 \left( \frac{5.1M_{\odot}^2 \text{ pc}^{-5}}{\Sigma_{\text{ISM}}\rho_{\text{ISM}}} \right) \left( \frac{M_c}{10^4M_{\odot}} \right)^{\delta} \text{ Gyr.}$$

where $\delta = 1 - 3\lambda$ with $R \propto M^\lambda$. Simulations of the mass–radius relationship suggest that the appropriate value of $\delta$ ranges from 0.2 for low-mass clusters to ~1 for the highest-mass (weakly disrupted) clusters (Gieles & Renaud 2016). In the latter case corrections due to adiabatic compression become so important that tidal shocks can destroy clusters in a single encounter (Miholics et al. 2017). Observations of nearby galaxies including M51, M33, and the SMC suggest a weak mass-radius relation ($\lambda \sim 0.1$ resulting in $\delta = 0.6–0.7$: Boutloukos & Lamers 2003). However, recent results from LEGUS show that the average $\lambda$ is 0.24, although the median cluster mass in the LEGUS sample is 1–2 orders of magnitude lower than the clusters studied here (Brown & Gnedin 2021).

Using observations of the molecular gas scale height ($H = 177$ pc), and GMC surface density ($\Sigma = 2.5 \times 10^3 M_{\odot} \text{ pc}^{-2}$) in the central regions of NGC 3256, as well as an average cluster mass of $10^{5.8} M_{\odot}$, we derive a disruption timescale of ~10 Myr (Wilson et al. 2019; Brunetti et al. 2021), which is comparable to the timescale over which we expect internal feedback processes to occur (~3–5 Myr). The upper limit represents the point where massive stars begin to die in supernova explosions injecting energy and momentum into their surroundings (Barnes et al. 2020; Chevance et al. 2022). This is contrasted against a disruption timescale for the outer disk of ~200–300 Myr, with an order of magnitude lower ISM density and approximately the same median cluster mass ($10^{5.8} M_{\odot}$).

Gieles & Renaud (2016) present an updated version of Equation (5) that additionally accounts for internal evolution of the cluster during this disruption phase as well as the velocity dispersion of the surrounding gas. Depending on the adopted mass–radius relationship this results in an increase in the
derived disruption timescale by a factor of ~3–30. For the central region of NGC 3256 we derive a disruption timescale of ~40 Myr for the inner disk and ~400 Myr of the outer disk adopting values for the velocity dispersion of the gas of 120 and 40 km s^{-1}, respectively (Brunetti et al. 2021).

Ultimately, we find that the disruption timescale from tidal shocks can be short enough to affect the age distribution of clusters with \( t < 1 \) Gyr in the central regions of LIRGs. Qualitatively, this difference corresponds to an increase in mass-dependent cluster disruption, where long-term cluster evolution in the central regions of LIRGs is primarily influenced by the external tidal field and ISM density within ongoing mergers. Finally, these results are consistent with a similar UV-optical study presented in Adamo et al. (2020) that looked at the cluster populations for a sample of six LIRGs, including NGC 3256. While not focusing on the age distribution directly, they note a lack of young lower-mass clusters in the inner region relative to their outer-disk cluster sample for this system.

5.1.2. Increasing SFR versus Increasing Cluster Destruction

An important assumption made in the interpretation of these age distributions is that they are the result of cluster disruption, rather than a large increase in the formation of clusters to the present day. This assumption is clearly adequate for quiescent star-forming galaxies, but may not be true in ongoing starbursts like the Antennae or even the central regions of M83. Chandar et al. (2017) used extinction-corrected GALEX FUV and 24 \( \mu \)m fluxes to derive SFRs averaged from 10–100 and 100–400 Myr for several starburst galaxies including NGC 3256, M51, and the Antennae. Combined with published color–magnitude diagram analysis for the LMC, SMC, NGC 4214, and NGC 4449, they demonstrate that the SFRs have not varied by more than a factor of ~2 for both the dwarf and starburst galaxies in their sample. There also appears to be no systematic trends in the average SFR with age, suggesting that strong variations in the cluster age distribution seen in these systems is likely the result of cluster disruption rather than increased formation. Finally, complete photometric coverage from the FUV to the FIR Pereira-Santaella et al. (2015) used the spectral energy distribution (SED) fitting code MAGPHYs (da Cunha et al. 2008) to derive the SFRs for ~30 local LIRGs. They find that, apart from Arp 299, sources classified as having an SF burst show global enhancements of ~2–4 in SFR, forming 1%–2% of the total stellar mass in the galaxy.

If the differences observed between the inner- and outer-disk age distributions in Figure 9 from 1–100 Myr are entirely due to an increase in the cluster formation rate (CFR), then the increase in \( \gamma \) of 0.7 would correspond to an increase in \( \Delta N/dt \propto \text{CFR} \) of 25 for clusters above the completeness limit \((10^5 M_\odot)\) of our inner-disk sample. While the exact relationship between SFR and CFR may vary in different galactic environments, it has been shown to be approximately linear and thus we take the two quantities proportional to one another (Johnson et al. 2017). The models presented in (Kruĳssen 2012) suggest that the CFR/SFR is ~ 30%–40% for regions with \( \Sigma_{\text{gas}} \sim 103 M_\odot \text{pc}^{-2} \), and therefore an increase in the CFR of 25 should be considered a lower limit for the required increase in SFR.

Using the F336W images as a proxy for the recent (10–100 Myr) SF activity we can make estimates of the surface density inside and outside the MIR size of each galaxy. Although the \( U \)-band continuum is not tied to the photospheric emission of the youngest stellar populations directly (as is the case for the UV), the errors are minimized for highly star-forming galaxies such as LIRGs (Kennicutt 1998). We find that the increase in F336W-traced SFR surface density is \( 6.2 \pm 1.1 M_\odot \text{yr}^{-1} \text{kpc}^{-2} \) and \( 3.5 \pm 0.4 M_\odot \text{yr}^{-1} \text{pc}^{-2} \) for NGC 3256 and IC 1623, respectively. These results are consistent with CALIFA IFU observations of IC 1623 which showed an extinction-corrected enhancement between 30 and 300 Myr of ~2 in the central half-light radius (Cortijo-Ferrero et al. 2017), which would correspond to a change in \( \gamma \) of 0.15–0.2.

Given the above, the most plausible explanation is that while the CFR in the central regions of NGC 3256 and IC 1613 are clearly increasing, the differences in the slope of the age distribution observed for inner- and outer-disk clusters suggests that cluster disruption plays a key role: clusters found in the inner regions of these LIRGs show greater disruption rates relative to SSCs identified in their outer disks. The magnitude of this difference is also larger than the differences observed for inner- and outer-disk clusters in other nearby normal galaxies, suggesting that the merging process is crucial for driving such extreme disruption rates (Adamo 2015; Hollyhead et al. 2016).

5.2. Mass Function

We consider the mass distribution of clusters in our LIRG sample over Regime 2 described in Section 4. When modeling the CMF we adopt a maximum-likelihood fitting technique as well as a bootstrap resampling of the posterior distribution functions for both a simple power-law model (PL) and a two component Schechter function of the form \( dN/dM \propto (M/M_t)^\alpha e^{(M/M_t)} \), where \( M_t \) is the truncation mass and \( \alpha \) is the overall power-law slope. In order to test the hypothesis of a mass truncation, we have fit the cumulative distribution function: 

\[
N(M' > M) = N_t \left( \frac{M}{M_t} \right)^{\alpha+1} - 1, 
\]

where \( N_t \) is the number of clusters more massive than \( 2^{1/(\alpha+1)} M_t \). We implement the IDL routine MSPECFIT, which has been used previously to study the mass functions of both GMCs and SSCs in galaxies in the Local Universe (Rosolowsky et al. 2007; Messa et al. 2018). A best-fit value for \( N_t \) with \( \alpha > 3\sigma \) significance will imply evidence for a truncation in the mass function at the truncation mass \( M_t \). In Table 5 we list the best-fit values to the cumulative distribution function for all five LIRGs, the three early stage systems, the two late-stage systems, and finally the inner- and outer-disk cluster samples, which are labeled all, early, late, inner, and outer, respectively.

In Figure 10 we show the best-fit PL and PL+ truncation models for the full sample. We find that clusters with ages \( t \leq 10^7.5 \) yr have \( \alpha \sim -1.45 \pm 0.03 \) and \( M_t = 10^{6.9} M_\odot \). However at such high values of \( M_t \) our ability to constrain this upper-mass truncation becomes challenging due to the low number of clusters expected above this limit. Indeed, apart from the All and Early stage distributions, which each have a \( N_t/\sigma_{N_t} > 3 \) and \( M_t > 10^6 \), we do not find evidence supporting a truncated power law in any of the remaining subsamples. Adamo et al. (2020) find evidence, albeit for 1/6 targets that the inclusion of older clusters with ages up to 100 Myr, can increase the significance of the PL+ truncation model to \( \geq 3\sigma \).
However we do not find that including older clusters in any of our subsamples increases the significance of the PL+truncation model such that we favor it over the simple PL model. Examining at the results for inner- and outer-disk clusters we see that the inner-disk clusters drive the trend seen in the larger data set in support of a truncated power-law model. Given that the inner disk has been shown to be a highly disruptive environment for young massive clusters, it is not unexpected to find stronger evidence of a truncation. Overall, the PL models for the inner- and outer-disk clusters agree within uncertainties. This is consistent with detailed results for another well-studied LIRG, Arp 299, which show differences in the derived $M_t$ of $\leq 2$ between the two galaxy nuclei and the extended disk (Randriamanakoto et al. 2019).

Finally, our value for the CMF is consistent with the luminosity functions derived from Paβ observations of LIRGs in GOALS Larson et al. (2020). By comparison, $\alpha$ is commonly measured to be $-2$ for lower-luminosity star-forming galaxies with an $M_t \sim 10^{13} M_\odot$ (Bastian 2008; Larsen 2010; Johnson et al. 2017). These results suggest that LIRGs are capable of forming relatively more massive clusters that what is seen in other nearby galaxies.

### 5.2.1. MS Dependence

Since U/LIRGs in the GOALS sample span the full range of merger stages, we can test if our explanation of cluster formation and destruction depends on the dynamical state of the galaxy. Haan et al. (2013), Kim et al. (2013), and Stierwalt et al. (2013) have classified the MS of each U/LIRG in the GOALS sample based on their morphological appearance at multiple wavelengths. These merger classification schemes run from pre-first passage to single coalesced nuclei. In order to search for changes in the cluster age and mass distributions as a function of merger stage, we separated the sample into early (classes 0–3: NGC 3256, IC 1623, NGC 7469) and late-stage (classes 4–6: Arp 220, NGC 6240) mergers.

In Figure 11 we show the CMF for Regime 2 for both the early and late-stage mergers and find that young star clusters in the early stage show a power-law distribution of $dN/dM \propto M^{-1.65\pm0.04}$ consistent with the slope for the full sample. However, when examining the slope for the late-stage mergers we find that it appears flatter ($\alpha = -1.42 \pm 0.13$). For the late-stage mergers we extend Regime 2 down to $10^{4.5} M_\odot$ given that these systems are not used in the inner- and outer-disk comparison, and that many of the clusters live outside the MIR size defined for these systems. This result suggests that late-stage mergers may be able to form massive clusters with an even higher efficiency (increased proportion of higher-mass clusters formed) than what has been observed for LIRGs involved in ongoing mergers. Indeed, the late-stage mergers are both ULIRGs with a median SFR that is $\sim 2 \times$ higher than the early stage mergers in our sample.

In order to quantify any differences in the age distributions for each merger stage we ran a K-S test comparing the normalized distributions of the early and late-stage mergers to the total sample (see Figure 12). We find that within our subsample of five LIRGs there is a $\sim 3\sigma$ difference in the age distribution of clusters between our early and late-stage mergers, with the latter showing a much larger fraction of old massive clusters. As we have shown in Figure 9, these clusters are more likely to survive in the outer disks of early mergers, where the effect of tidal shocks is less severe compared to the inner disks. Hence, the fact that we see a higher fraction of older clusters in late-stage mergers, where most clusters are found in the outer disks, can be directly attributed to the higher survival rates of older clusters in the outer disks that allow them to accumulate over the course of the merger.

Given the above, we prefer a scenario where the flat CMF for young clusters is due primarily to an increase in the formation

| Table 5 | Results From MSPECFIT for PL and PL+Truncation |
|---------|------------------------------------------------|
| Sample  | $N_t$ | $\sigma_{N_t}$ | $M_t$ | $\sigma_{N_t}$ | $\alpha$ | $\sigma_{\alpha}$ |
| All     | 24.22 | 7.43          | 8.15e+06 | 5.74e+06 | -1.45 | 0.03 |
| All-PL  |        |               |        |        | -1.66 | 0.03 |
| Early   | 23.73 | 7.61          | 8.52e+06 | 2.51e+06 | -1.45 | 0.03 |
| Early-PL|        |               |        |        | -1.65 | 0.02 |
| Late    | 0.491 | 2.02          | 6.62e+07 | 1.68e+07 | -1.42 | 0.09 |
| Late-PL |        |               |        |        | -1.51 | 0.13 |
| Inner   | 32.83 | 13.3          | 6.38e+05 | 1.71e+06 | -1.60 | 0.06 |
| Inner-PL|        |               |        |        | -1.58 | 0.08 |
| Outer   | 3.63  | 2.65          | 1.32e+07 | 1.81e+07 | -1.65 | 0.06 |
| Outer-PL|        |               |        |        | -1.65 | 0.06 |

Note. $N_t$ is the number of clusters more massive than $2^{(\alpha+1)} M_\odot$, where $M_t$ is the truncation mass in the Schechter function given in $M/M_\odot$, $\alpha$ is the slope of the PL or the PL component of the Schechter function. We note that a 3σ significance for the PL+truncation model $N_t/\sigma_{N_t}$ is only reached for the All and Early stage cluster subsamples.

Figure 10. The stacked mass distribution function for all five galaxies. The red line represents the maximum-likelihood fit to the data for a power-law (PL) model, with analytic Schechter function (PL+truncation) fit to the empirical distribution overlaid in blue. Although the evidence for a truncation is marginal (3σ), the values obtained for the $M_t$ are significantly larger than what is observed for lower-luminosity star-forming galaxies in the Local Universe. These results are consistent with the luminosity function derived from Paβ observations of LIRGs in GOALS (Larson et al. 2020), as well as detailed observations of Arp 299 (Randriamanakoto et al. 2019).
of massive clusters, which results in a flattened mass distribution in Regime 2 relative to the early stage mergers. However there is a significant population of old massive clusters which have survived the progressive increase in the destruction of lower-mass clusters (depending on the exact value of $\delta$) throughout the course of the merger. Ultimately, higher SFRs, stronger tidal shocks, and increasing pressures throughout a galaxy merger all play a role in shaping the evolution of the cluster age and mass distributions relative to nearby low-luminosity star-forming galaxies.

6. Summary

HST WFC3/UVIS (F336W) and ACS/WFC optical (F435W and F814W) observations for a sample of 10 LIRGs in the GOALS sample were obtained (see Figures 1 and 13–21). These observations have been used to derive the ages, masses, and extinctions of the SSCs contained within the five nearest systems in order to examine the cluster properties in extreme starburst environments relative to those in nearby, lower-luminosity star-forming galaxies. The following conclusions are reached:

(1) We have detected 1027 clusters throughout the disks of these five LIRGs. These clusters have S/N $\geq 3$ in all three filters and deconvolved FWHMs as measured by ISHAPE of $\lesssim 3$ pixels, corresponding to a median physical size of $\sim 22$ pc.

(2) The derived cluster age distribution implies a disruption rate of $dN/d\tau \propto \tau^{-0.5 \pm 0.2}$ over $10^6 < \tau < 10^8$ and for cluster masses $\geq 10^5 M_\odot$. This is consistent with the general framework that ongoing mergers destroy clusters at a much higher rate due to the high external pressure induced from a strong tidal field. The measured $\gamma$ is steeper than what has been observed in lower-luminosity star-forming galaxies in the Local Universe.

(3) Differences in the slope of the observed cluster age distribution between inner- and outer-disk clusters ($\Delta \gamma \sim 0.7$ dex) provides some of the clearest evidence to date of location-dependent cluster destruction, and that this destruction outweighs the increase in the CFR within the central region. Not only does this effect appear to be ubiquitous in the central regions of LIRGs, but the magnitude of this effect is amplified even relative to strong gradients of cluster disruption observed in normal star-forming galaxies in the Local Universe.
(4) The derived cluster masses imply a CMF for our sample galaxies of \( dN/dM = M^{-1.66+/-0.03} \) with marginal evidence for a PL+truncation at \( M_t \sim 2 \times 10^6 M_\odot \) for early stage mergers, which dominate the full sample. This trend appears to be driven in large part by the inner disk, where the extreme environment acts to rapidly destroy clusters at a rate which exceeds expectations from a \(-2\) power law at the highest masses.

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Figure 19. Same as Figure 1.

Figure 20. Same as Figure 1.

Figure 21. Same as Figure 1.

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