GEMINI SPECTROSCOPIC SURVEY OF YOUNG STAR CLUSTERS IN MERGING/INTERACTING GALAXIES. II. NGC 3256 CLUSTERS

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ABSTRACT

We present Gemini optical spectroscopy of 23 young star clusters in NGC 3256. We find that the cluster ages range from few to $\sim$150 Myr. All these clusters are relatively massive $[(2-40) \times 10^5 \, M_\odot]$ and appear to be of roughly $1.5 \, Z_\odot$ metallicity. The majority of the clusters in our sample follow the same rotation curve as the gas and hence were presumably formed in the molecular-gas disk. However, a western subsample of five clusters has velocities that deviate significantly from the gas rotation curve. These clusters may either belong to the second spiral galaxy of the merger or may have formed in tidal-tail gas falling back into the system. We discuss our observations in light of other known cluster populations in merging galaxies, and suggest that NGC 3256 is similar to Arp 220, and hence may become an ultraluminous infrared galaxy as the merger progresses and the star formation rate increases. Some of the clusters that appeared as isolated in our ground-based images are clearly resolved into multiple subcomponents in the HST ACS images. The same effect has been observed in the Antennae galaxies, showing that clusters are not often formed in isolation, but instead tend to form in larger groups or cluster complexes.

Subject headings: globular clusters: general — globular clusters: individual (NGC 3256)

Online material: color figures

1. INTRODUCTION

In the prevailing picture of hierarchical early-type galaxy formation, small fragments form first and then merge into larger and larger pieces until the system resembles a large, smooth, anisotropically supported elliptical galaxy. The study of globular clusters has an important role to play in testing the predictions of this theory and in answering the question about if and when the bulk of this merging took place. Studies of the Galactic globular cluster system have been fundamental to the development of ideas on how the Galactic halo, and perhaps the entire galaxy, has been assembled from merging fragments (Searle & Zinn 1978; Da Costa & Armandroff 1995). Studies of extragalactic cluster systems have revealed evidence for multiple populations of clusters and allow us to use them to connect the various phases of galaxy evolution.

GCs in galaxies more distant than about a megaparsec cannot be resolved into stars, even with the Hubble Space Telescope (HST). However, the fact that they contain simple stellar populations means that their integrated properties can be used to determine metallicities and ages. Surveys of large numbers of globular cluster systems reveals that $>90\%$ of all E’s have bimodal color distributions, and only $10\%-20\%$ in S0’s (Kundu & Whitmore 2001a, 2001b). Almost all galaxies host a GC population with a peak in their color distribution at $V - I = 0.95$. Available metallicity measurements suggest that these are old, metal-poor clusters like the Galactic halo GCs (Geisler et al. 1996). The second peak is redder than the first and implies that the red GCs are more metal-rich. In general, these GCs are also old, but the age-metallicity degeneracy in broadband colors makes age differences hard to determine unless the GCs are rather young (see Whitmore et al. 1997).

There are several competing scenarios for how the globular cluster systems of galaxies formed. Ashman & Zepf (1992) predicted that the merger of two disk galaxies would produce an elliptical with a bimodal GC color distribution. The blue clusters are Galactic-halo like clusters from the progenitor galaxies. These clusters would have formed like those in the Galaxy, perhaps from the accretion of dwarf galaxies with large numbers of GCs. Dwarf elliptical galaxies were efficient at forming clusters and these clusters resemble those in the Galactic halo (Miller et al. 1998). In the Ashman & Zepf scenario, the red population is formed during the merger process from the metal-enriched gas in the disks. The formation of new clusters also alleviates the problem that ellipticals have specific globular cluster frequencies (number per unit luminosity) about a factor of 2 higher than spirals do (Schweizer 1987). An alternative scenario is that all the clusters were formed “in situ,” in a multiphase collapse of a single potential well (Forbes et al. 1997), similar to the early monolithic collapse picture of the formation of the Galaxy (Eggen et al. 1962). In this case, the metal-poor clusters form first in the halo and metal-rich clusters form later during the final collapse, or recollapse, stages from metal-enriched gas. Both these scenarios fit into the overall picture of hierarchical galaxy formation, but they differ as to when the bulk of the merging takes place.

An important result of the merger scenario is that the merger of two spiral galaxies can cause the formation of many young...
star clusters in the starburst resulting from the collision of the two gas disks (Schweizer 1987; Ashman & Zepf 1992). The creation of star clusters may alleviate the problem that elliptical galaxies have specific globular cluster frequencies \( (S_g, \text{ the luminosity-weighted number of GCs}) \) about a factor of 2 higher than in spirals. The evidence is growing that significant numbers of star clusters are formed during galaxy mergers. \( HST \) observations of NGC 1275 (Holtzman et al. 1992; Carlson et al. 1998) were some of the first to find very luminous blue objects with the properties of young GCs in a galaxy that may have had a recent merger. Large young cluster populations with ages between 10 and 500 Myr were soon found in obvious merger remnants like NGC 7252 (Whitmore et al. 1993; Miller et al. 1997), NGC 3921 (Schweizer et al. 1996), NGC 3256 (Zepf et al. 1999), and NGC 4038/4039 (Whitmore & Schweizer 1995; Whitmore et al. 1999). Spectra of the brightest young clusters in NGC 1275 (Zepf et al. 1995) and NGC 7252 (Schweizer & Seitzer 1993, 1998) confirmed that the clusters were between 0.5 and 1 Gyr old with roughly solar metallicities. Since these clusters are many internal crossing times old, they would seem likely to survive to become the red GC populations of the faded merger remnants (e.g., Whitmore et al. 1997; Goudfrooij et al. 2001a).

These observations allow us to proceed to the next level of understanding the evolution of globular cluster systems; we must understand in more detail how star clusters form and how systems of star clusters evolve. It is thought that star clusters are formed in high-pressure environments (Harris & Pudritz 1994; Elmegreen & Efremov 1997), be they caused by the collisions of giant molecular clouds or by a general pressure increase in the gas surrounding molecular clouds. Observations of the Antennae can now provide some key parameters about the state of the ISM during clusters formation and the feedback produced by the young clusters. Zhang et al. (2001) compared the locations of different cluster populations with emission from the ISM at wavelength from X-rays to radio and found that the youngest clusters are associated with molecular cloud complexes and may lie in regions of high \( \mathrm{H} \alpha \) velocity dispersion. However, the small velocity dispersion of the clusters among themselves strongly suggest that it is not high-velocity cloud-cloud collisions that drive cluster formation, but the general pressure increase experienced by gas during the merger (Whitmore et al. 2005). Feedback, seen in the form of \( \mathrm{H} \alpha \) bubbles around young-cluster complexes, may enhance this process.

An interesting question is how globular cluster systems evolve. Most very young star-cluster systems studied in merging galaxies have power-law luminosity functions of the form \( M^{-2} \) (e.g., Schweizer et al. 1996; Miller et al. 1997; Whitmore et al. 1999; Zhang & Fall 1999). However, the luminosity (or mass) function of old globular clusters has a log-normal shape with a peak at \( M_g^* \sim -7.3 \) \((\sim 10^5 M_\odot)\); Harris 1991). Therefore, either the initial mass function of star clusters was different in the past, perhaps due to low metallicity, or a substantial fraction of the young clusters must be destroyed for the young mass functions to evolve into what we see in older systems. A great deal of theoretical work has gone into globular cluster destruction processes (e.g., Fall & Rees 1977; Gnedin & Ostriker 1997; Vesperini 1997, 1998; Fall & Zhang 2001). The main processes that can destroy globular clusters are stellar evolution, two-body relaxation, dynamical friction, and disk shocking, or if the clusters formed in gas-rich environments, interactions with GMCs can play a significant role (Gieles et al. 2006). The models of Fall & Zhang (2001) predict that there may be radial variations in the peak of the mass function within a galaxy and that the peak will shift to higher masses with time. Many of these processes depend on the relative velocities of the clusters and field stars and on the cluster orbits.

In this paper we present some first results of a large spectroscopic survey of star clusters in merging and interacting galaxies. We focus on 23 bright star-cluster candidates in the main body of NGC 3256 observed with GMOS on Gemini South. Other targets in our survey, to be presented in future papers, include NGC 4038/39 (the Antennae), NGC 6872, Stephan’s Quintet, and M82.

NGC 3256 was classified as an intermediate-stage merger in Toomre’s list of nearby merging systems (Toomre 1977). The merger is more advanced than systems like NGC 4038/39, in which the two original disks are still distinct, but the two nuclei (Moorewood & Oliva 1994; Norris & Forbes 1995; Lira et al. 2002; Neff et al. 2003) have not merged yet either. They have a separation in projection by \( 5'' \), or \( \sim 900 \) pc. Hence, NGC 3256 is not as relaxed a system as NGC 7252 is. The outer parts of the system are characterized by shell-like features and two extended tidal tails that are typical of merging galaxies. The body of the system is crisscrossed by dust lanes that enshroud an on-going starburst: the far-infrared luminosity, X-ray luminosity, and star formation rate are the highest of all the systems in the Toomre sequence. This starburst has created over 1000 star clusters in the central region (Zepf et al. 1999) as well as in the tidal tails (Knierman et al. 2003; Trachco et al. 2007, hereafter Paper I).

The current paper is organized as follows: § 2 describes the observations. In §§ 3 and 4 we derive the ages, masses, extinctions, metallicities, and line-of-sight velocities of the 23 clusters. Finally, § 5 discusses and summarizes the results.

NGC 3256 is located at \( \alpha_{J2000.0} = 10^h27^m51.3^s, \delta_{J2000.0} = -43\degree54'14'' \) and has a recession velocity relative to the Local Group of \( v_{\mathrm{helio}} = +2804 \pm 6 \) km s\(^{-1}\), which places it at a distance of 36.1 Mpc for \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\). At that distance, adopted throughout the present paper, \( 1'' = 175 \) pc. The corresponding true distance modulus is \( (m-M)_0 = 32.79 \). Because of the low Galactic latitude of NGC 3256, \( b = +11.7\degree \), the Milky Way foreground extinction is relatively high, \( A_V = 0.403 \) (Schlegel et al. 1998), whence the apparent visual distance modulus is \( V - M_V = 33.19 \).

2. OBSERVATIONS AND REDUCTIONS

Imaging and spectroscopic observations of star clusters in NGC 3256 were made with GMOS-S in semesters 2003A and 2004A. The data were obtained as part of two Director’s Discretionary Time programs, GS-2003A-DD-1 and GS-2004A-DD-3. Our images cover the typical GMOS-S field, which measures approximately \( 5.5' \times 5.5' \). They were obtained through the \( g' \) and \( r' \) filters. Four GMOS masks with slitlets were used for the spectroscopic observations. We used the B600 grating and a slitlet width of 0.75", resulting in an instrumental resolution of 110 km s\(^{-1}\) at 5100 Å. The spectroscopic observations were obtained as eight individual exposures with exposure times of 3600 s each. Our spectroscopy of 70 cluster candidates yielded only 26 objects that were bona fide star clusters in NGC 3256. Of these, three are located in the western tidal tail and have been described in Paper I. In the present paper we focus on the 23 star clusters located in or near the main body of NGC 3256. Table 1 lists these star clusters. Column (1) gives the adopted cluster identification, columns (3) and (4) the coordinates, and columns (5) and (6) the absolute magnitudes \( M_g \) and \( M_r \) and their errors. The magnitudes have been corrected for Galactic extinction, but not for any internal extinction.

Figure 1 shows an \( HSTACS \) image of the main body of NGC 3256, with the observed candidate clusters marked by their identification numbers.
The basic reductions of the data were done using a combination of the Gemini IRAF package and custom reduction techniques, as described in the Appendix.

3. DERIVATION OF CLUSTER PROPERTIES

The derivation of cluster properties (such as age and metallicity) based on the strengths of stellar absorption lines through optical spectroscopy is not straightforward, due to degeneracies between age, metallicity, and extinction. Multiple studies have addressed this problem (e.g., Schweizer & Seitzer 1998; Schweizer et al. 2004; Puzia et al. 2005), and here we extend previous studies.

Although in some of our cluster spectra the strengths of stellar absorption lines cannot be measured due to strong emission lines, the fluxes/equivalents width (EW) of the emission lines of the surrounding H II region can be measured. In these cases a chemical abundance can be estimated for the H II region, in which the cluster has recently formed, from line-emission measurements (e.g., Kobulnicky & Kewley 2004; Kobulnicky & Phillips 2003; Vacca & Conti 1992). This abundance is expected to be the same as that of the young stellar cluster itself, and hence complements abundance measurements of the absorption-line-dominated clusters.

Below we outline the method adopted in the present study.

3.1. Extinction, Age, and Metallicity

3.1.1. Absorption-Line Clusters

We first select the model spectra by Bruzual & Charlot (2003, hereafter BC03) and by González-Delgado et al. (2005, hereafter GD05). Then we smooth the model spectra to the same resolution as the observed spectra. Then we compare the cluster spectra with the models for clusters of solar metallicity, to which we have applied various amounts of extinction (using the Galactic extinction law from Savage & Mathis 1979), $A_V = 0 - 10$ in steps of 0.1 mag. We select the best fitting model via minimized $\chi^2$, Modelbest(age, $A_V$), and correct the observed spectrum for the derived extinction $A_V$ to yield Cluster$_{obs, ext}$.

This procedure was carried out for the BC03 and GD05 models independently, and we note that for individual clusters the...
results are very similar. Due to the finer grid of young ages in the GD05 cluster models we adopted these for our further analysis. We then inserted the extinction-corrected spectra into the IDL implementation of the Penalized Pixel Fitting routine (pPxF) of Cappellari & Emsellem (2004).1 This routine determines the best implementation of the Penalized Pixel Fitting routine (pPxF) of GD05 cluster models we adopted these for our further analysis.

We measured the line strengths of the hydrogen Balmer lines as well as the indices defined by Schweizer & Seitzer (1998) for young stellar populations. To make the measurements, we used the routine Indexf (Cardiel et al. 1998), which finds the line strengths and errors by performing Monte Carlo simulations on the spectra, using information derived from the error spectra (i.e., the placement of the continuum bands and noise in the data). Indexf was run on Clusterobs instead of Clusterobs,ext. The reason for this is that we found that the measured index strengths of the Clusterobs,ext depended on the signal-to-noise ratio (S/N) of the spectrum. This is shown in Figure 2, where we plot the nine measured indices of an observed cluster (T130 in the Antennae, which is our best S/N cluster and has identical setup and was observed in the same way) degraded to various S/N’s. The open symbols represent the measurement of the line strength for each index when Indexf is run on Clusterobs,ext, while the filled symbols represent the measurements carried out on Clusterobs,ext. The lines show the average index strength for the five highest S/N measurements. From this numerical experiment we conclude that the measurements on Clusterobs,ext reproduce those of Clusterobs,ext for high S/N, but remain accurate to S/N < 10, while measurements on Clusterobs,ext begin to show significant scatter below S/N ≈ 15.

However, we note that with this adopted procedure the measured Hβ index is always systematically off. The models never reproduce an absorption feature on the red side of the line. In

![Fig. 2.—Tests showing the effect of the S/N on the measured line indices. We used a high-S/N cluster spectrum, degraded its S/N ratio, and then measured line indices. Open symbols mark measurements made from the observed spectrum (corrected for extinction) directly, while filled symbols represent measurements made from a template spectrum derived for the cluster using the pPxF technique. Solid lines represent averages of the highest S/N experiments on the observed cluster spectrum (Clusterobs,ext). For further details, see text. [See the electronic edition of the Journal for a color version of this figure.]](image-url)
addition, similar tests were performed where we inserted the model spectrum (i.e., treating the models as observations, degrading them in S/N and finding the indices). These tests showed a systematic offset in the H\beta/C13A measurements although the other lines were well reproduced. Therefore, we removed both the H\beta/C12 and H\beta/C14A indices from our list for further analysis.

Using Indexf we also measured the line strengths of the GD05 models, for all model ages and metallicities. The age and metallicity of each observed cluster was then determined by comparing its line indices to that of models, weighted by the respective errors, in a least squares sense. In order to test the robustness of this technique we added random errors to the measured indices (using a normal distribution with a dispersion corresponding to the 1σ measurement error) and redid the analysis. This was done 5000 times for each cluster. The final age was then determined by creating a histogram of the derived ages and fitting a Gaussian to it (in logarithmic space), where the adopted age is the peak age of the Gaussian and its error is the standard deviation. The cluster metallicity was found by simply averaging the derived metallicity of the 5000 runs. Examples of this process are shown in Figure 3.

Finally, to check the consistency of our results, we plotted the spectra of Cluster_{obs, ext} and the best fitting model (i.e., the model closest in age and metallicity). If the fit was not satisfactory, then we began the entire process again, eliminating the initially derived extinction from the options. This was the case for only a handful of young clusters that were initially fit with low extinctions and higher ages. Two examples of cluster spectra are shown in Figure 4.

The black lines are the Cluster_{obs, ext} Spectra, while the red and green lines represent the best fitting model (age, metallicity) and the residual (Cluster_{obs, ext} – template – constant). T1002 in the right panel is clearly very young and has, as such, still ionized gas associated with it. In the observed and residual spectra, we clearly see emission lines from Hγ, Hβ, and [O iii] λλ4959, 5007.

As a further test of the derived cluster ages, we chose a subset of indices that are good at distinguishing between the age and metallicity of a cluster. For illustrative purposes, Figure 5 shows the [MgFe] index (Thomas et al. 2003) plotted versus the H\beta/C13 index for both the GD05 and BC03 models. The indices from the models are also shown. From these diagrams we check for consistency in the derived ages and metallicities of the clusters. The derived ages, extinctions, and metallicities are given in Table 1.

### 3.1.2. Emission-Line Clusters

For the youngest clusters with little or no absorption features in their spectra the task is much easier. First, we assign ages to these clusters of less than 10 Myr, due to the presence of large amounts of ionized gas around the cluster. Age dating can be refined to some degree by the presence or absence of Wolf-Rayet features (e.g., cluster T2005; see Fig. 6); however, that is beyond the scope of the present paper. The extinction of these cluster is calculated from the H\beta to H\beta emission-line ratio.

We adopt the chemical analysis method from Kobulnicky & Kewley 2004 (hereafter KK04) to determine the metallicity. We measure the EW ratio of the collisionally excited [O ii] λλ3727
and [O \text{iii}] \lambda 4959, 5007 emission lines relative to the H\beta recombination line (known as R23) and [O \text{iii}] \lambda 4959, 5007 relative to [O \text{ii}] \lambda 3727 (known as O32), along with the calibrations on KK04 (their Fig. 7, upper branch) and the solar abundances by Edmunds & Pagel (1984). Instead of the traditional flux ratio, the KK04 method uses EW ratios that have the advantage of being reddening independent.

As can be seen in Table 1 the metallicities found for absorption- and emission-line clusters agree well, giving us confidence in the robustness of the diagnostic methods and results.

### 3.2. Masses

In order to calculate the mass of each cluster we compared the photometry ($g'$ and $r'$) with the BC03 SSP models, assuming a Chabrier (2003) stellar initial mass function and solar metallicity. We then used the age dependent mass-to-light ratio from the models to convert our derived absolute magnitudes (observed magnitudes corrected for Galactic extinction, internal extinction, and the assumed distance modulus) to mass. Errors on the mass were estimated from the derived errors on the age and photometric errors. Systematic errors (e.g., errors associated with the distance to NGC 3256) are not included. Table 3 gives the derived masses of the clusters.

### Table 3

| ID      | $D^a$ | $cz$(CO) (km s$^{-1}$) | $cz$(hel) (km s$^{-1}$) | $\Delta cz$ (km s$^{-1}$) | Mass ($10^5 M_\odot$) |
|---------|-------|------------------------|------------------------|--------------------------|------------------------|
| T88     | 1     | ...                    | 2821.1 ± 17.9          | ...                      | 8.3 ± 2.6              |
| T96     | 1     | 2725:2845.7            | 2845.7 ± 17.4          | +120:1.7                 | 1.7 ± 0.9              |
| T99     | 0     | 2660                   | 2786.9 ± 23.7          | +126                     | 49.5 ± 1.8             |
| T112    | 0     | 2735                   | 2711.4 ± 56.2          | -23                      | 45.0 ± 2.4             |
| T116    | 0     | 2715                   | 2741.4 ± 15.9          | +26                      | 13.8 ± 7.3             |
| T141    | 0     | 2740                   | 2736.4 ± 14.2          | -4                       | 6.7 ± 3.5              |
| T161    | 0     | 2740                   | 2743.6 ± 17.0          | +3                       | 11.0 ± 5.8             |
| T199    | 1     | 2820                   | 2865.5 ± 10.2          | +45                      | 3.4 ± 0.3              |
| T201    | 1     | ...                    | 2840.2 ± 26.1          | ...                      | 2.3 ± 0.7              |
| T306    | 0     | 2815                   | 2813.2 ± 14.1          | -2                       | 19.9 ± 0.1             |
| T343    | 0     | 2895                   | 2993.2 ± 45.8          | +128                     | 18.6 ± 1.6             |
| T356    | 0     | 2895                   | 2914.2 ± 7.6           | +19                      | 121.1 ± 6.4            |
| T374    | 0     | 2882.4 ± 24.1          | ...                    | ...                      | ...                   |
| T492    | 0     | 2910.3 ± 95.9          | ...                    | ...                      | ...                   |
| T654    | 0     | 2912.8 ± 25.6          | +22                    | 1.3 ± 0.7                |
| T661    | 0     | 2802.8 ± 25.9          | +17                    | 35.5 ± 8.3               |
| T744    | 0     | 2911.7 ± 77.1          | +61                    | 2.1 ± 0.5                |
| T761    | 0     | 2842.2 ± 25.6          | +25                    | 4.6 ± 2.4                |
| T779    | 1     | 2880                   | 2959.0 ± 10.3          | +79                      | 1.4 ± 0.7              |
| T799    | 0     | ...                    | 2883.9 ± 41.2          | ...                      | 1.6 ± 0.8              |
| T1002   | 0     | ...                    | 2857.5 ± 91.8          | ...                      | 0.2 ± 0.1              |
| T1078   | 1     | ...                    | 2772.7 ± 9.1           | ...                      | 159.0 ± 6.6            |
| T2005   | 0     | 2865                   | 2871.3 ± 5.8           | +4                       | 140.4 ± 7.4            |

*a In this column 0 = disk; 1 = not disk.

*b Complexes.
3.3. Velocities

In the case of absorption-line clusters, we used the IRAF task rvsao.xcsao for the determination of the redshift from the individual spectra, using three different types (A, O, B) of radial-velocity standard stars (HD 100953, HD 126248, and HD 133955) observed at the same resolution as the clusters. The three template stars were employed to reduce the systematic errors introduced by the effect of template mismatch when computing the redshift using the cross-correlation technique. For the emission-line clusters, velocities were measured from the observed emission lines using the IRAF task rvsao.emsao. In both cases the velocities were corrected to heliocentric (see Table 3).

Figure 7 shows the positions of the observed clusters within NGC 3256 (shown in contours to highlight its main features), marked with the cluster metallicities, extinctions, ages, and velocities, respectively.

4. CLUSTER KINEMATICS: TWO POPULATIONS?

There is strong evidence that the molecular gas in the central region of NGC 3256 lies in a disk that rotates (Sakamoto et al. 2006). The rotation axis of this gas disk lies approximately along the north-south direction, which is also the apparent minor axis of the main optical disk. It is interesting to compare the observed cluster radial velocities to the molecular-gas velocities at each cluster’s position.

Figure 8 shows the measured radial velocities of the clusters plotted versus the cluster right ascension (R.A.), corresponding roughly to their projected position along the major axis. Superimposed is the rotation curve for the molecular gas measured by Sakamoto et al. (2006). The figure suggests that the majority of the clusters are still associated with the gas from which they formed (see Table 3). At least 15 of the 23 observed clusters show clear evidence of corotating with the molecular-gas disk. Hence, we will refer to these clusters as “disk clusters.”

4.1. Origin of the Disk

Sakamoto et al. (2006) suggest that the molecular-gas disk may have formed during the merger of the parental spiral galaxies. By using the ages of the disk clusters we can put a lower limit on the longevity of the disk. These ages range from recently formed (e.g., T76: <10 Myr) to 100 Myr old (T112). Thus, the molecular-gas disk must have existed for at least 100 Myr.
The NGC 3256 merger probably began approximately \(~500\) Myr ago (English et al. 2003). It is not yet completed, as the two nuclei have yet to merge (Moorwood & Oliva 1994; Norris & Forbes 1995; English & Freeman 2003). Therefore, if the observed molecular-gas disk and clusters formed during the merger, the disk must have begun forming early in the merger. Sakamoto et al. (2006) compare the NGC 3256 system to that of NGC 7252, a recently formed merger remnant which also hosts a molecular-gas disk. However, in contrast to the situation in NGC 7252, the two nuclei of NGC 3256 have yet to merge, which may disrupt any current large-scale gaseous disk (Barnes 2002). Hence, the two merger systems may not presently be comparable. An alternative hypothesis, however, is that the observed gas disk belongs to one of the two original spiral galaxies, so that the observed disk clusters simply formed in that disk as part of the enhanced star formation activity caused by the gravitational interaction.

In either scenario we would expect older star clusters to be present as well. The fact that they are not detected in the present study is readily explained by selection bias: we selected the brightest clusters, which tend to be young, for spectroscopy.

4.2. Nondisk Clusters

In the western section of the galaxy we find five clusters that have velocities apparently inconsistent with an extrapolation of the molecular-gas disk velocities. The clusters have ages between \(<7\) Myr (e.g., T96) and \(~150\) Myr (e.g., T1078). These clusters may belong either to the other spiral disk (which may lie behind the observed disk in projection) or to material that has become dissociated from the original disks due to the interaction/merger. These clusters are also located spatially near the beginning of the western tail (see Fig. 1 in Paper I). A detailed comparison with the H\(_\text{i}\) position-velocity diagram of English et al. (2003) shows that the H\(_\text{i}\) tail begins approximately 45” to the west of the observed clusters. However, as Figure 9 shows, these clusters are coincident spatially and kinematically with H\(_\text{i}\) gas that has a very different radial-velocity distribution from that of the molecular gas. The H\(_\text{i}\) radial velocities reach a minimum near the CO rotating disk and a maximum at the kinematic center of NGC 3256, whereupon they begin dropping again inside the western tidal tail. One possible interpretation is that the gas-velocity anomaly, noted already by English et al. (2003), is caused by gas falling back into the central parts of NGC 3256 from one of the tidal tails (perhaps the eastern one).

Two other clusters located closer to the observed galactic center stand out in terms of their kinematics. These clusters (T779 and T343) have velocities larger than that expected if they were part of the rotating molecular-gas disk (although T343 is only incompatible with the disk velocity at the 1.5 \(\sigma\) level). Both clusters are very young and have only modest extinction (\(A_V = 0.4–0.8\)). We note that these two clusters are located in a part of the galaxy where there is a rather large scatter in the measured velocities of the clusters (e.g., T201, T343, T356, T779), and thus their deviation may be part of a larger trend. It is possible that we are seeing a heating or beginning destruction of the disk due to the interaction/merger, and that star formation is proceeding from an ordered phase, i.e., in a disk, to that of a more chaotic phase where dispersion dominates over rotation.

5. DISCUSSION

5.1. Environment of the Clusters

Some of the emission-line clusters that appeared isolated in our ground based images are clearly resolved into multiple subcomponents in the HST/ACS images. The same phenomenon has been observed in the Antennae galaxies (e.g., Whitmore & Schweizer 1995; Bastian et al. 2006a), showing that clusters are often not formed in isolation but instead tend to form in larger groupings, or cluster complexes. These complexes are thought to be a short-lived phenomenon as they disperse on short timescales, although merging within the central parts of the groupings is possible (e.g., Fellhauer & Kroupa 2002). The remnants of such cluster-cluster mergers are an attractive means to form extremely large clusters, such as W3 and W30 in NGC 7252 (Kissler-Patig et al. 2006). Hence, it is possible that in a few cases (which are in very crowded regions, e.g., T2005 and T116) we may be overestimating the mass of our apparent “cluster” if, in fact, it is made up of several clusters.

5.2. Star/Cluster Formation Rates

NGC 3256 contains the most molecular gas among the merging galaxies and merger remnants of the Toomre sequence (1.5 \(\times\) \(10^{10}\) \(M_\odot\); Casoli et al. 1991; Aalto et al. 1991; Mirabel et al. 1990, from Zepf et al. 1999). Thus, there will be plenty of gas left to fuel a massive starburst when the nuclei merge (e.g., Mihos & Hernquist 1996). At that time, one may expect the star/cluster formation rate to increase substantially (between 3 and 10 times depending on the encounter parameters and the time to nuclear coalescence; Cox et al. 2006). The present star formation rate in NGC 3256 is estimated to be \(33\) \(M_\odot\) yr\(^{-1}\) from the far-infrared luminosity (Krierman et al. 2003). It is known that a tight relation between the most massive star cluster in a galaxy and the galaxy’s star formation rate exists (e.g., Larsen 2004). In NGC 3256 we find about 10 clusters with masses in excess of \(10^6\) \(M_\odot\). If the star (cluster) formation rate does increase substantially as the nuclei merge, we may expect the NGC 3256 system to create clusters with masses significantly above \(10^7\) \(M_\odot\), such as those found in NGC 7252 and NGC 1316 (e.g., Schweizer & Seitzer 1998; Maraston et al. 2004; Bastian et al. 2006b).
Arp 220 is comparable to NGC 3256, as it also has an extremely high infrared luminosity, is thought to have formed through a merger, and has two distinct nuclei separated by only 300 pc in projection (Scoville et al. 1998; Wilson et al. 2006). The nuclei in NGC 3256 are separated (in projection) by ~900 pc indicating that it is possibly slightly younger (in terms of merger stage) than Arp 220. The star formation rate in Arp 220 (240 M_{\odot} yr^{-1}; Wilson et al. 2006) is approximately 7 times higher than that in NGC 3256. It is then possible that NGC 3256 is currently poised to enter the regime of ultraluminous infrared galaxies (ULIRGs) as its star formation rate increases due to the merging of the two nuclei. Arp 220 also closely follows the relation between global star formation rate in the galaxy and the magnitude of the most massive cluster (Wilson et al. 2006), arguing further that NGC 3256 is going to form clusters in excess of 10^7 M_{\odot}.

5.3. Metallicities

As Figure 10 shows the young clusters in the NGC 3256 system appear to have rather high metallicities, with the average being ~1.5 Z_{\odot}. This was also found for the clusters in the tidal tails described in Paper I. We do not see any major spread in metallicities among our clusters and, specifically, no differences coming from ages or emission versus absorption. The fact that the majority of these young clusters formed in a disk and their age spread is small fits in nicely with the notion of a normal starburst process.

6. COMPARISON OF NGC 3256 WITH OTHER MERGING GALAXIES

Many of the clusters observed to be associated with the molecular gas are quite massive (>10^5 M_{\odot}), have survived for many internal crossing times (t_{cr} \approx 2–4 Myr) and are therefore gravitationally bound. This justifies calling them young globular clusters. Such young globulars have been found in many merging galaxies, from beginning mergers (e.g., NGC 4038/39; Whitmore & Schweizer 1995) to completed mergers (e.g., NGC 1316; Goudfrooij et al. 2001a). The formation of these clusters is thought to trace the major star formation events in these galaxies and they must form with approximately the same kinematics as the gas out of which they form. It is therefore interesting to compare the NGC 3256 cluster population to those of younger (in terms of dynamical stage) and older merging systems.

The majority of the cluster population of the beginning merger NGC 4038/39 is still unambiguously confined to the disks of the two progenitor galaxies (Whitmore et al. 2005; Bastian et al. 2006a; Paper I). Therefore, NGC 3256 appears to predominately fall into this category (see § 4).

Older systems, on the other hand, such as NGC 3921 (Schweizer et al. 2004), NGC 7252 (Schweizer & Seitzer 1998), and NGC 1316 (Goudfrooij et al. 2001b) are all characterized by the kinematics of their clusters being dominated by noncircular, halo-type orbits. When does the transition happen? It will be interesting to determine whether the majority of the star formation happens in the disks of the progenitors and their orbits are subsequently randomized (i.e., turned into pressure supported systems rather than rotational supported systems), or whether the star formation events that precede the destruction of the galactic disks pale in comparison with the star formation rate during and after the destruction.

Note that shortly after the merger a gaseous disk can reform around the nucleus of the merger remnant, which can harbor subsequent star formation (e.g., NGC 7252: Miller et al. 1997; Wang et al. 1992), although such star formation appears to occur at a much lower intensity than previous star-forming episodes during the merger.

7. SUMMARY AND CONCLUSIONS

We have studied the ages, metallicities, masses, extinctions, and velocities of 23 clusters in NGC 3256 based on the Lick index system in conjunction with CO and H i maps. The main results are as follows:

1. The clusters have rather high metallicities, with the average being ~1.5 Z_{\odot} (Fig. 10) and are massive, with masses in the range (2–40) x 10^5 M_{\odot}. The ages of the clusters are between a few and ~150 Myr.

2. There is strong evidence for a rotating molecular-gas disk in NGC 3256 (Sakamoto et al. 2006). The majority of the clusters in our sample follow the same rotation curve as the gas and hence were presumably formed in the molecular-gas disk. However, a western subsample of five clusters has velocities that deviate significantly from the gas rotation curve. These clusters may either belong to the second spiral galaxy of the merger or may have formed in tidal-tail gas falling back into the system.

3. Although the merger began ~500 Myr ago (English et al. 2003), we found the clusters to be \approx 150 Myr old. Since there are still two distinct nuclei marking the presence of two galaxies, we conclude that the gas disk probably belongs to one of the galaxies and is not yet a disk of pooled gas produced in the merger itself. Presumably clusters older than the ones present in our sample do exist in NGC 3256. However, these older clusters would not have been selected as spectroscopic candidates due their fainter magnitudes (i.e., only the brightest candidates were selected).

4. By comparing of the NGC 3256 cluster population with other known galactic mergers, we suggest that this system is akin to Arp 220, although slightly dynamically younger. If this is the case, we may expect the star/cluster formation rate to increase significantly as the two galactic nuclei merge. This in turn may push NGC 3256 into the category of ULIRGs (it is currently a LIRG). Due to the expected large increase in the star/cluster formation rate, a few clusters above 10^7 M_{\odot} are predicted to form before this merger is through.
5. Some of the clusters which appeared as isolated in our ground-based images are clearly resolved into multiple sub-components in the HST ACS images. The same effect has been observed in the Antennae galaxies, showing that clusters are often not formed in isolation, but instead tend to form in larger groups or cluster complexes.

With these new results, i.e., cluster ages, metallicities, extinctions, and kinematics, as well as recent CO and H I maps, N-body simulations of this merger would be the best way to fully understand this wealth of data. The models would have important implications for (globular) cluster formation and destruction as well as the star formation history of the merger (through the age/metallicity of the clusters) with respect to other mergers like the Antennae, NGC 7252, and Arp 220. Finally, the details of the models may present important implications of the formation of ellipticals galaxies through the major mergers of spiral galaxies.

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APPENDIX

REDUCTION OF GMOS DATA

The data were reduced using the Gemini IRAF package. The individual tasks used at each of the reduction steps are listed below in parentheses. The raw GMOS images (three CCDs read out using one amplifier each) are multiextension FITS (MEF) files with one primary header unit, containing all the usual header information, and three pixel extensions, one for each of the detectors.

A1. IMAGING DATA

Mean bias frames were created combining all the available bias frames taken during each of the GMOS-S observing runs (task gbias).

Twilight flat fields were created from all the available twilight frames taken during each of the GMOS-S observing runs (giflat). The overscan section of the images was trimmed off, and the images were bias-subtracted and flat-fielded using the task gireduce. The three image extensions in each exposure were then mosaicked into a single image extension in which the shifts and rotations between the three CCDs have been removed (gmosaic).

The images were registered and co-added using the task imcoadd, and they have been calibrated using the science exposures taken under photometric conditions.

A2. SPECTROSCOPIC DATA

We are using the MOS mode with approximately 25 spectra per mask. Each set of data include an arc and flat taken along with each science exposure and spectral dithers. Bryan Miller developed our own script-driven pipeline MOSPROC, based on Gemini IRAF scripts and custom IDL routines. The Gemini package scripts have been modified, mainly to improve the propagation of data quality planes.

1. MOSPROC:

(a) Bias subtraction for spectra, flats, and arcs: The bias subtraction for the spectroscopic data was done in the same way as for the imaging. Quartz-halogen (QH) flat fields exposures were taken during the night, either after or before the science exposures. To run through MOSPROC, the science, arcs, and flats frames were first bias subtracted using the task gareduce.

(b) Bad pixel mask: A bad pixel mask was constructed from the QH flats, taking into account the known bad pixels in each CCD, and masking the existing emission lines in the spectral QH lamps that came from the IR diffuser.

(c) Flat-field correction The QH flats were overscan trimmed and bias-subtracted like the imaging data and the mask definition file (MDF) was added as a table extension to the MEF. The MEF contains the locations of the slits in the focal plane and is used for bookkeeping during the remaining reduction. The flats were normalized by fitting a high-order polynomial to each line to remove the shape of the quartz lamp but leaving the fringe pattern at the red end of the spectra gsfat. The task gareduce was then used to divide the science data by the flat fields.

The resulting science exposures still have three extensions, but now trimmed, bias-subtracted, and flat-fielded.

(d) Wavelength calibration and distortion correction: The wavelength calibration was determined from CuAr lamp spectra taken either before or after the science exposures. The dispersion function was fit with a sixth-order polynomial that gave a typical rms error of 0.3 Å (gswavelength). Within each slitlet the position of each arc line with spatial position is used to rectify and wavelength calibrate each two-dimensional (2D) spectrum (gstransform).

(e) Cosmic-ray removal: Cosmic rays were identified and removed using a Laplacian edge detection algorithm (van Dokkum 2001). The locations of the cosmic rays are recorded in the 2D data quality image for each slitlet.

The spectra were then traced, background-subtracted, and extracted using gsextract, a wrapper for twodspec. apall, to allow the handling of MEF files. The spectra were traced using a fifth-order polynomial and averaging every 50 pixels in the dispersion direction. Background subtraction was done by fitting a second-order polynomial with 3 σ rejection to a region perpendicular to the trace. The variance and background spectra were saved to help with the error estimation.
Quantum efficiency (QE) correction: The QE as a function of wavelength for the three GMOS CCDs can differ by up to about 5% at the given wavelength. If this difference is not corrected then spectra can have noticeable jumps at the gaps between the CCDs. We have measured the relative QE of CCD1 and CCD3 with wavelength compared with CCD2 using OH flats taken at 25 nm intervals from 350 to 700 nm. The corrections are applied to the data using an IRAF script called qecorr.

2. Correction for slit losses:

The GMOS instruments do not have atmospheric dispersion correctors and in general the MOS spectra were not taken with the slits parallel to the parallactic angle. Therefore, there are wavelength-dependent slit losses due to the difference between the parallactic angle of each exposure and the position angle of the slits. In order to combine the spectra from different exposures properly these differences must be corrected. We calculate the slit losses based on measured image quality, slit width (0.75″), and the P.A.–parallactic angle difference using the method of Filippenko (1982).

3. Relative flux calibration and reddening:

a) Relative flux calibration: The relative instrument spectral response function was determined using observations of a flux standard star. Spectra were taken at central wavelengths of 400, 500, and 600 nm so that the combined sensitivity function covered the full wavelength range of the MOS spectra. The standard spectra were reduced in exactly the same way as the MOS spectra. The sensitivity function was computed using the IRAF task gsensfunc and this was applied to the MOS spectra using the task gscalibrate.

As the last step, we combined the individual spectra using our IRAF task called gcombine. This uses the final data quality planes to mask the chip gaps and other bad pixels and then scales and averages the spectra using gcombine.

b) Reddening: The interstellar extinction along the line of sight toward NGC 3256 is $A_V = 0.403$. The final calibrated spectra were corrected using the empirical selective extinction function from Cardelli et al. (1989) included in the task noao.onedpec.deredden.

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