GIANT H II REGIONS IN THE MERGING SYSTEM NGC 3256: ARE THEY THE BIRTHPLACES OF GLOBULAR CLUSTERS?

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ABSTRACT

CCD images and spectra of ionized hydrogen in the merging system NGC 3256 were acquired as part of a kinematic study to investigate the formation of globular clusters (GCs) during the interactions and mergers of disk galaxies. This paper focuses on the proposition by Kennicutt & Chu that giant H II regions (GHRs), with an Hα luminosity greater than $1.5 \times 10^{40}$ ergs s$^{-1}$, are birthplaces of young populous clusters (YPCs). Although, compared with some other interacting systems, NGC 3256 has relatively few (seven) giant H II complexes, these regions are comparable in total flux to about 85 30 Doradus–like giant H II regions (GHRs). The bluest, massive YPCs (Zepf et al.) are located in the vicinity of observed 30 Dor GHRs, contributing to the notion that some fraction of 30 Dor GHRs do cradle massive YPCs, as 30 Dor harbors R136. If interactions induce the formation of 30 Dor GHRs, the observed luminosities indicate that almost 900 30 Dor GHRs would form in NGC 3256 throughout its merger epoch. In order for 30 Dor GHRs to be considered GC progenitors, this number must be consistent with the specific frequencies of globular clusters estimated for elliptical galaxies formed via mergers of spirals (Ashman & Zepf). This only requires that about 10% of NGC 3256’s 900 30 Dor GHRs harbor YPCs, which survive several gigayears and have masses $> M_{\odot}$.

Key words: galaxies: individual (NGC 3256) — galaxies: interactions — globular clusters: general

1. INTRODUCTION

1.1. Motivation for Kinematic Observations

Based on observations of starburst activity and the large amounts of molecular gas in interacting galaxies, Schweizer (e.g., 1988) suggested that merger events provide an ideal environment for the formation of massive star clusters. Theoretical support that these would evolve into globular clusters (GCs) was provided by Elmegreen & Efremov (1997), who argued that massive bound clusters preferentially form in a high-pressure environment, such as that created during a starburst. Starbursts frequently are observed in galaxy–galaxy interactions and mergers, presumably enhanced by tidally induced shocks (Larson 1987). Other suggestions of how interactions may provide the dynamical phenomenon necessary to produce young populous clusters (YPCs; also known as super–star clusters) and how these will subsequently evolve into GCs have been described, for example, by Elmegreen (1993), Boily, Clarke, & Murray (1993), and Murray & Lin (1993).

HST searches of interacting and merging systems have been spectacularly successful in finding compact blue objects that are likely to be YPCs formed during the interactions and mergers. Large numbers of blue compact objects were detected in the interacting galaxy NGC 4038/39 (Whitmore & Schweizer 1995) and merger remnants NGC 1275 (Carlson et al. 1998; Faber 1993; Holtzman et al. 1992) and NGC 7252 (Whitmore et al. 1993). The brightest of these clusters have the attributes expected of proto–globular clusters (Whitmore 2003).

Underlying all of this is the hope that, as the merging systems settle to form an elliptical galaxy, the YPCs will survive to contribute to its rich globular cluster system (GCS). An important observational element is missing from this picture: are the kinematics of the YPCs at the present time consistent with their ultimate spatial distribution in the cluster system of the final elliptical remnant? To answer this question, we need to compare velocity data for the YPCs (or for their progenitors) with the kinematics of associated features in the hydrodynamical simulations of merging spirals.

To make this comparison, GC progenitors need to be identified. Assuming YPCs evolve into GCs, some possible sites for GC formation during mergers include giant H II regions and the detached H I fragments and gas clumps within the extended tidal features found around merging galaxies (e.g., Duc & Mirabel 1994). We would like to eventually test whether the spatial and velocity distributions of these GC progenitor candidates are consistent with the statistical distribution and kinematics of small-scale condensations in the hydrodynamical models of merging galaxies. We have collected data relevant to measuring the masses and the spatial and velocity distributions of H I and H II regions within galaxy systems that sample the range of galaxy–galaxy interaction stages leading to a merger remnant. This paper, as well as a companion paper by English et al. (2003, hereafter Paper II), describes observations of one merging system, NGC 3256.

1.2. Globular Cluster Formation Scenarios

Searle & Zinn (1978) proposed that GCs form in small fragments, which are subsequently accreted by the parent galaxy. Their fragments are presumably the low-mass end of the hierarchy of fluctuations that aggregate to form a
spiral system. In major mergers another source of fragments are those torn from interacting galaxies; falling back into the potential well of the remnant galaxy, they experience star formation due to tidally induced shocks and contribute their resultant GCs to the emerging elliptical. This globular cluster formation scenario motivated the neutral hydrogen observations of NGC 3256 that will be presented in Paper II.

The ionized hydrogen observations presented here were motivated by Kennicutt & Chu’s (1988) suggestion that giant H II regions are the birthplaces of YPCs such as the young globular clusters seen in the Magellanic Clouds. We consider the possibility that giant H II region formation is enhanced in the disks of interacting spirals during the interaction. The associated YPCs would be subsequently redistributed, along with the other components of the two disks involved, as the merger of the parent galaxies proceeds (e.g., Schweizer 1995). This is supported by the clustering of YPCs in NGC 4038/39. The youngest star clusters spatially cluster together more than the intermediate-age clusters (which are apparently associated with tidal tails) and than the old GCs (distributed mostly throughout the disk), suggesting mixing has occurred over several orbits (Zhang et al. 2001). This is also consistent with the observation that the clusters in giant ellipticals have a roughly similar spatial distribution to the diffuse light distribution. (Although in some ellipticals the GC distribution is a little flatter than the light distribution; Harris 1993. In others, like NGC 1399, the cluster and light distributions are almost identical in slope; Harris & Hanes 1987.)

The mass spectrum of GCs in ellipticals results from the initial mass spectrum during the cluster formation epoch and the effects of subsequent dynamical evolution. Hence, in the context of this globular cluster formation scenario, it is interesting that the observed mass spectrum of GCs, with masses greater than \(10^2 \, M_\odot\) in elliptical galaxies is fitted by a near universal power law (Harris & Pudritz 1994), which has the same slope as the giant H II region mass spectrum (e.g., Kennicutt et al. 1989; McCall et al. 1996).

### 1.3. The Specific Frequency of Merger Remnants

The specific frequency \(S_N\) of globular clusters is the number of GCs per unit absolute magnitude \(M_V = -15\) of galaxy luminosity (Harris & van den Bergh 1981). The range of \(S_N\) observed for elliptical galaxies covers an order of magnitude (Harris 1993) and its value for spiral galaxies can be an order of magnitude lower than for cD ellipticals (which are at the high extreme).

Schweizer (1988) proposed that the \(S_N\) of a remnant elliptical would be larger than the value derived from the sum of the GCs populations of the parent galaxies due to GCs formation during mergers. Ashman & Zepf (1993) determined the number of GCs per unit stellar mass, using a characteristic \(M/L_V\) for each morphological type. They find that normal (i.e., non-cD) elliptical galaxies have more than twice as many GCs per unit stellar mass as spirals. Therefore, even the construction of normal ellipticals via the merger of spirals would require the formation of GCs in the merger process.

Of course, this would also require GCs to form in preference to noncluster stars in the merger. While this is theoretically plausible (e.g., Elmegreen & Efremov 1997) and vast numbers of YPCs are clearly formed in mergers like NGC 4038/9, there is no direct evidence that this is so. Still, NGC 1275 provides an example of a system with a high \(S_N\) (\(\sim 27\)), and Carlson et al. (1998) find that it will remain larger than that of the old GC population even if the majority of the low-mass clusters are destroyed.

We should comment here on an important paper by Forbes, Brodie, & Grillmair (1997), who examined the color distribution of GCs in ellipticals. In galaxies with a high specific frequency of GCs (mostly cD ellipticals), they found that the excess GCs are mostly metal-poor. This is not consistent with forming the high specific frequency of GCs through mergers of spiral galaxies with near-solar metallicity. But it does not argue against formation of YPCs in mergers: this is clearly observed to happen. The Forbes et al. result suggest that the bulk of GC formation in cD ellipticals may have occurred during the early phase of hierarchical merging, while the mean metallicity was still low. That is, the GCs may have formed through the early merging of a large number of relatively unevolved fragments, rather than through the later merging of more chemically evolved galaxies.

### 1.4. NGC 3256

NGC 3256 is a nearby (2820 km s\(^{-1}\)) merging system which is experiencing a spatially extended and highly luminous starburst (~3 \(\times 10^{11}\) L\(_\odot\); Sargent et al. 1989). The 10 \(\mu\)m luminosity of the visible H\(_\alpha\) nucleus (~2 \(\times 10^{10}\) L\(_\odot\)) rivals that of Seyfert galaxies (Graham et al. 1984). The system has another “nucleus” 3″ to the south, obscured by dust but detected in nonoptical wavelengths, such as: 3 cm (Norris & Forbes 1995); near-infrared K-band (e.g., see P. MacGregor in Paper II; Lipari et al. 2000); and X-ray (Lira et al. 2002). This system also has a star-forming complex in its ‘disk’, an arc of giant H II regions, and 2 extended tidal tails. The two X-ray nuclei, along with the diffuse X-ray emission, support the scenario that NGC 3256 is powered by a starburst rather than an AGN (Lira et al. 2002). Therefore we tentatively assume that NGC 3256 has two cores (one from each parent galaxy) that are on the verge of merging.

Lipari et al. (2002) argue that NGC 3256 is the result of a multiple merger with the disk star forming complex as the third nucleus. Since there are only two tidal tails, they suggest that either an on-going merger system encountered a third galaxy or that two gas-rich spirals plus a minor galaxy merged simultaneously. These cases, for our order of magnitude estimates, can be replaced by two-galaxy prograde interaction scenario.

In Paper II we estimate the dynamical timescale associated with the neutral hydrogen component of the tails and compare our observations with numerical simulations of starbursts in galaxy mergers which generate elliptical remnants (e.g., Mihos & Hernquist 1994). In these models the timescale since the last pericenter approach of the parent galaxies through to coalescence is about 500 Myr, comparable to our estimate of the dynamical time (~500 h\(^{-1}\) Myr) since pericenter in the observed NGC 3256 system. If the model parent galaxies contain dense bulges, a strong starburst is also produced at about 500 Myr postpericenter. Although the K-band luminosity profile of NGC 3256 is not yet the \(r^{1/4}\) distribution of a fully relaxed system, the profile is consistent with a merger phase in which the cores of two galaxies are about to coalesce (Moorwood & Oliva 1994).
Subsequent violent relaxation would cause this system to have the structure of an elliptical galaxy in its final merger state (Schweizer 1986).

Hernquist & Bolte (1993) examine the GCSs produced in simulations of mergers of two disk galaxies. The surface brightness profile of the model GCSs are also well fitted by the observed $r^{1/4}$ law. They argue that one of the sites of new cluster formation will be in the inner regions of the merger remnant, because a large fraction of disk gas is driven to each disk’s center and subsequently the cores of the disks merge (Barnes & Hernquist 1992, Mihos & Hernquist 1994). Since NGC 3256 is approaching the merger stage (see the merger sequence by Toomre 1977), it is thus not surprising that H II region formation is enhanced in the galaxy’s disk. Again, the inner disk gas would provide the high pressure environment to produce bound clusters according to Elmegreen & Efremov (1997). And, though all may not be bound, Zepf et al. (1999) find several hundred compact, blue clusters likely to be young clusters within the 7 arcsec$^2$ central region.

Our photometry (§ 2) shows that, although NGC 3256 has relatively few H II regions compared with some other interacting systems, these regions are comparable in flux to about 85 30 Doradus–like H II regions (§ 3). Since the 30 Doradus nebula contains the YPC NGC 2070 (Meylan 1993), we label as “30 Dor GHRs” any giant H II regions with luminosities greater than or equal to $1.5 \times 10^{56}$ ergs s$^{-1}$ (Kenneicutt & Chu 1988). We present two-dimensional spectra (§ 2) used to compare the velocity distribution of H II regions in this merging system with numerical models; these extend spatially beyond the spectra of Lipari et al. (2000) (§ 3). We estimate the number of YPCs that could be born between the last closest approach of the parent galaxies and the currently observed epoch in § 3. We summarize in § 4 that NGC 3256 is an emerging elliptical galaxy that is producing a population of YPCs consistent with the specific frequencies of GCs that would be expected for elliptical remnants formed via mergers of spiral galaxies (Ashman & Zepf 1993).

2. OBSERVATIONS, REDUCTIONS, AND DATA ANALYSIS

2.1. CCD Images

2.1.1. Observations and Reductions

On 1991 February 25 we obtained $2 \times 300$ s broadband $I$ and $2 \times 600$ s narrowband H$\alpha$ exposures of NGC 3256 and E region standard field 5 (Graham 1982) with the 1 m telescope at Siding Spring Observatories (SSO). The EEV CCD has $832 \times 1152$ pixels, pixel scale of 0.575, readout noise 4 e$^{-}$ and gain 1 e$^{-}$ ADU$^{-1}$. The seeing was better than 2$''$. The central wavelength of the narrowband filter is 6594 Å, its FWHM 52 Å and its equivalent width 24 Å. At the redshift of NGC 3256, the $[N\,\text{II}]$ $\lambda$6583 emission line lies in the wing of the filter passband where its contribution to the image is negligible.

We first corrected the nonlinearity of this CCD ($<1.5\%$ at 18,000 ADU to 6% at the extrapolated value of 70,000 ADU). Subtracting a fit to the overscan region of every image reduced the low-level time-dependent horizontal bias patterns caused by electronic pickup. The dark current of this CCD is negligible, so only bias images were subtracted. The target images were flat-fielded using dome and twilight flat fields for each individual filter. The processed images of the galaxy were shifted to a common position and combined for each filter with an algorithm that rejects cosmic rays. Image editing corrected residual bad columns and pixels.

For the continuum images, we used the $I$ band, thus avoiding contamination of the continuum images by H$\alpha$ and $[N\,\text{II}]$ emission lines which are included in the $R$-band. To scale the H$\alpha$ and $I$-band images, we used aperture photometry of the target galaxy itself. Assuming that the outer regions (i.e., envelope) of the galaxy disk do not contain a significant amount of H$\alpha$ emission, the $I$-band image was initially scaled such that the $I$-band envelope matched the intensity of the envelope in the narrowband H$\alpha$ image. We then experimented with scaling to the H$\alpha$ continuum within the inner 11$''$ radius. We adopted the scaling that avoided negative H$\alpha$ flux in this H$\alpha$ region zone when the scaled $I$-band image was subtracted from the narrowband image to form a continuum-free H$\alpha$ image. This is likely to underestimate the true H$\alpha$ flux.

The slit spectra of the H II regions have an equivalent width in H$\alpha$ $\geq 80$ Å, confirming that they are bright. The spectra also indicate that our underestimate in H$\alpha$ photometry is $\leq 15\%$.

2.1.2. Flux Calibration

The H$\alpha$ flux density of our narrowband images was calibrated (in ergs s$^{-1}$ cm$^{-2}$) using observations of five standard stars in the E-region, with the zero points given by Bessell (1990, 1992). The absolute flux density through the narrowband filter was determined by interpolating the broadband zero points to the central wavelength of the filter and using the equivalent width of the filter to calculate the integrated continuum light for each standard star over the bandpass.

We used a circular aperture of 4$''$ to measure the observed sky-subtracted count rates for each star. These were corrected for atmospheric extinction using the mean air mass of the observations. The mean extinction coefficient for the H$\alpha$ filter, $k_{6596} = 0.085$, was estimated by interpolation between the mean broadband coefficients determined at SSO by A. Schröder (1991, private communication). The estimated error of this calibration is about 6%.

2.1.3. H II Region Photometry

Each irregularly shaped giant H II region complex in NGC 3256 was outlined with a polygon. The sky-subtracted count rate, determined from the annular sky aperture marked on Figure 1, was corrected within each polygon for atmospheric extinction and for Galactic absorption. The Milky Way absorption ($A_{6596} = 0.35$ mag) was determined using the color excess for NGC 3256 (Burstein & Heiles 1984) and interpolating through average interstellar extinction values $A_{\lambda}/E(B-V)$ (Savage & Mathis 1979). We did not attempt to correct for extinction within NGC 3256 itself. This H$\alpha$ flux was subsequently corrected for the transmission of the filter at the wavelength (6625 Å) associated with the redshift of the galaxy (2820 km s$^{-1}$; see determination in § 3.1). The total H$\alpha$ energy output, presented in Table 1, was derived using $H_0 = 100\ h$ km s$^{-1}$ Mpc$^{-1}$.

We did not attempt to divide up large complexes into apparent subcomponents, since our goal is to estimate whether the complexes are comparable to 30 Doradus in their H$\alpha$ flux. The compromises in polygon shape due to the proximity of other H II regions provide the largest uncertainty in the flux estimate ($1 \sigma \sim 17\%$), but this is insignificant for our comparisons with the flux of 30 Doradus.
Fig. 1.—Photometry of H II regions. The underlying Hα image is continuum subtracted. The annulus marks the region from which the mode sky value per pixel was determined. The polygons mark the areas measured. Those designated B1 through B7 are treated as H II regions and are described in Table 1. Comparisons with positions of Hα emission knots and X-ray sources in other projects are in Table 3. The area of B8 lies close to an optically obscured radio source. The inner radius of the annulus is 43″.

| Label | R.A.  | Decl.  | Velocity (km s\(^{-1}\)) | Hα Flux (10\(^{-13}\) ergs s\(^{-1}\) cm\(^{-2}\)) | Total Luminosity (10\(^{40}\) h\(^{-2}\) ergs s\(^{-1}\)) |
|-------|-------|--------|--------------------------|---------------------------------|-----------------|
| B1    | 10 27 51.1 | -43 54 15.0 | 2820.0 | 18.61 | 17.7 |
| B2    | 10 27 51.7 | -43 54 13.9 | 2907.0 | 26.53 | 25.3 |
| B3    | 10 27 52.8 | -43 54 11.7 | 2888.0 | 3.28 | 3.1 |
| B4    | 10 27 52.3 | -43 54 03.1 | 2881.0 | 0.97 | 0.9 |
| B5    | 10 27 50.6 | -43 54 10.4 | 2722.0 | 17.57 | 16.7 |
| B6    | 10 27 50.1 | -43 54 21.8 | 2741.0 | 8.76 | 8.3 |
| B7    | 10 27 49.5 | -43 54 33.2 | 2740.0 | 0.69 | 0.65 |

Notes.—See Fig. 1 for H II region labels. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds (J2000.0). The velocities are heliocentric and the formal error in velocity for these measurements is 7 km s\(^{-1}\). However, the velocity is that measured at the position on the DBS slit that lies closest to the center of the polygonal region used in CCD photometry; the difference between the tabulated velocity and the velocity at the center of the H II region can be as large as 20 km s\(^{-1}\). The photometry is described in § 2.1.3; corrections to the flux density compensate for atmospheric extinction, interstellar medium absorption in the Milky Way, and filter transmission losses. The total luminosity is the Hα flux over 4π sr at a distance of v\(_{\text{systemic}}/100 \ h \ km \ s^{-1} \ Mpc^{-1}\).
2.2. Hα Spectra

2.2.1. Observations

In order to determine the velocities of the H II regions, long-slit spectra were acquired at SSO using the double beam spectrograph (DBS) and photon counting array (PCA) at the Nasmyth focus of the 2.3 m telescope on 1991 March 8 and 9. The red 1200 line mm\(^{-1}\) grating gave a dispersion of 0.4 Å (~19 km s\(^{-1}\)) pixel\(^{-1}\), a FWHM resolution of about 1 Å, and a total wavelength range of about 300 Å. The slit width was 1.4 and the seeing about 2.00. In the spatial direction each pixel corresponds to 0.66 resulting in a useful slit length of about 330 Å.

To place the slit precisely, we placed one end of the slit on one of three stars near the interacting system (labeled “A,” “B,” and “C” in Fig. 2). Using this star as a pivot point, the spectrograph was rotated to various position angles on the sky. For each position angle a number of H II regions lay along the slit and hence produced a long-slit spectrum, which contained spectra for a number of emission-line objects as well as the continuum of the fiducial star (which provides a spatial reference point).

Exposures were typically 1000 s. A neon lamp was observed before and after every target spectrum. This allowed us to correct for the small flexure in the DBS as it rotated to maintain constant position angle on the sky. In order to ensure linearity of the detector in the flat-field exposures, we took quartz lamp spectra at rates less than 0.1 Hz pixel\(^{-1}\).

2.2.2. Hα Long-Slit Reductions

PCA data have no bias, and cosmic rays are rejected in hardware. Therefore, before wavelength calibration it was only necessary to flat-field the images as usual, using quartz lamp spectra: sky flats provide the correction for vignetting along the slit.

The wavelength calibrations, determining dispersion solutions, and rebinning to linear wavelengths used standard procedures (Massey et al. 1992). We did not correct for distortions in the spatial direction, since these were insignificant at the accuracy required by our study. We subtracted the background only when night sky OH lines lay very close to the redshifted H II emission lines.

To measure the radial velocities, we summed over three rows (~2", to match the seeing) and determined the center

![Fig. 2.—Velocity field of the ionized gas in NGC 3256. The underlying image is the ionized hydrogen data acquired using the SSO 1 m telescope. The spectroscopic data were acquired using the SSO 2.3 m telescope, the double beam spectrograph (DBS), and the photon counting array (PCA). Each “line” consists of the velocity values at a slit position. Red indicates receding velocities; blue indicates approaching velocities. The construction of this map is detailed in § 2.3. The stars used as fiducial pivot points for the DBS slit positions are labeled.](image-url)
of the Hα emission-line with a single-Gaussian fitting routine. We then stepped up one row, again summed three rows, and determined the central velocity of the Hα emission at this new position. This was repeated for all sections in the two-dimensional spectrum containing emission.

The PCA has an intrinsic semiperiodic fringing pattern, which changes slowly with time. Flat fielding removed most of this pattern. We unsuccessfully attempted to remove the remaining fringing by two-dimensional Fourier filtering, and the residual coherent noise ultimately limited the attainable signal-to-noise ratio and dominated the error in our velocity measurements, which increased with a decrease in emission intensity. To estimate this error empirically, we produced a calibration curve, using the sky lines in a set of night sky spectra. A spline curve was fitted to a plot of (error in measured wavelength) versus (median intensity of sky production) as described in §2.2.1. The error increases with decreasing counts to 18 km s\(^{-1}\) for peak intensities of about 10 counts pixel\(^{-1}\).

### 2.3. Velocity Field Analysis

An optical velocity field image of H\(\text{II}\) regions, Figure 2, was constructed by editing the H\(\alpha\) CCD image such that the heliocentric velocity values were substituted at the image pixel coordinates associated with the positions of the DBS slit. Gaps in the resultant DBS slit map, due to the difference in scale (arcsec pixel\(^{-1}\)) between the DBS and CCD images, were assigned interpolated velocity values. A typical positional uncertainty in the velocity field image is about 1 CCD pixel (0\('\)57). Due to the long exposure times, the DBS spectra were more sensitive than the imaging to diffuse emission. This results in velocity field data in regions without H\(\text{II}\) region peaks in the image.

The velocity field image was color edited to heighten the contrast of consecutive velocity value bins. The range of color bins is nearly linear, with each bin spanning 33.5 km s\(^{-1}\). The full color range was chosen to maintain the convention “red corresponds to redshift and blue corresponds to blueshift.”\(^1\) To create the intervening velocity range, the red and blue extrema were blended together such that the neutral gray bin in Figure 2 contains the heliocentric systemic velocity value.

The data from the horizontal slit position (associated with fiducial star A) are also presented in plot format (Fig. 3) in order to provide an indication of the galaxy’s velocity curve. Since the inclination of this galaxy is close to face-on, we have not attempted to deproject the data. Even when multiple Gaussian features were present in the one-dimensional spectra, they have been assigned an average velocity; the errors given are flux dependent errors (see §2.2.2) and do not reflect the range in velocity that these features span.

Also in Table 1 we present the heliocentric velocities corresponding to the point on the DBS slit that is closest to the center of each polygon used in the photometry (see Fig. 1). The difference between a polygon’s center and the position of the peak intensity of the H\(\text{II}\) region can be up to a few arc-seconds. Also, the slit positions generally did not pass directly through the center of the H\(\text{II}\) region. A comparison of the two slits that pass near the northern nucleus indicates that the velocities tabulated in Table 1 may differ from the mean velocity of a given H\(\text{II}\) complex by up to 20 km s\(^{-1}\).

### 2.4. Relationship to Other Data

These H\(\alpha\) images and spectra have in some respects been superseded by data acquired by Lipari et al. (2000). Their H\(\alpha\) image from the ESO New Technology Telescope is also used by Lira et al. (2002), who calibrated the flux (to within a factor of 2) of the Lipari et al. image, using the Lipari et al. long-slit spectroscopy of several H\(\text{II}\) knots. However, Lira et al. only report a total flux \((~2 \times 10^{-11} \text{ergs cm}^{-2}\ \text{s}^{-1})\) in an aperture with a 41″ diameter. Lipari et al. (2000) measured the H\(\alpha\) flux of H\(\text{II}\) knots via spectroscopy, effectively subdividing our selection of H\(\text{II}\) regions without measuring all the flux per region. For example, they present the flux of regions labeled R1, R2, and R4, but not of R8 and R9, although all of these would be in our regions B1 and B2; see Table 3. Although our measurements are therefore difficult to compare, their R7 region’s H\(\alpha\) flux differs from our measurement of B6 by 8%.

Our spectra are included not only for completeness sake but also because the resolution is 34 km s\(^{-1}\) (with errors ranging from 7 to 18 km s\(^{-1}\)) compared with the Lipari et al. (2000) instrument resolution of 90 km s\(^{-1}\) (errors ranging from 15 to 30 km s\(^{-1}\)). Additionally Lipari et al. only present velocity field maps with a width of 60″. Researchers, particularly those simulating the interactions between galaxies, may find our 330″ long slit provides useful information on almost all radii associated with the ionized hydrogen emission component of this galaxy and that our velocity field reveals interesting anomalies beyond the inner region (e.g., redshifted emission in the tail to the southwest in Fig. 2.)
3. RESULTS

3.1. Velocity Curve and the Dynamical Mass

Visual inspection of Figure 2 shows large-scale rotation, in the same sense as the rotation observed in the neutral hydrogen data (Paper II). However the velocity behavior of the optical disk appears less disturbed by the merger activity than do the H\textsc{i} arms.

The peculiar morphology of NGC 3256, the uncertainty of its center, the position angle of the major axis, and its near face-on inclination make it difficult to extract an accurate deprojected circular velocity curve. Figure 3 shows a velocity curve from a spectrum with the slit at position angle (P.A.) of 90°. Examination of H\textalpha\ features in Figure 2 shows that the turnover points in the velocity curve are representative of the velocity range of the system. The value at the midway point between the turnover peaks is 2820 ± 11 km s\(^{-1}\), and the velocity difference, \(\Delta V\), gives a rough estimate of the projected rotation velocity, \(v_{\text{circ}} = \Delta V/2 \approx 107 \pm 11\) km s\(^{-1}\).

This agrees with the Feast & Robertson (1978) estimate of the systemic velocity and rotation amplitude (using P.A. = 100°). Lipari et al. (2000) (using P.A. = 90°, however only for an inner region 40° square), and with the H\textsc{i} position-velocity (PV) diagram shown in Paper II. (We note that the distribution of H\textsc{i} in the PV diagram means that the rotation amplitude is significantly larger than the separation of the H\textsc{i} horns in the integrated H\textsc{i} profile also shown in Paper II.)

Assuming that the rotation curve is flat, we estimate that the mass within radius \(r\) is \(M(r) = 3.2 \times 10^{4} [v_{\text{circ}}(\text{km s}^{-1})]^2 r(\text{arcsec})^{-1} M_{\odot}\). This is no more than an order-of-magnitude estimate, because the system is unlikely to be in centrifugal equilibrium at this stage. Dynamical mass limits are given in Table 2 for a few radii associated with structural or kinematic features.

3.2. H\textsc{ii} Regions and Globular Clusters

Our goal in this section is to consider whether the H\textsc{ii} regions observed in NGC 3256 could be GC progenitors. For an ionized hydrogen region to be a GC progenitor, in the sense of Kennicutt & Chu (1988), we expect it to have a rich star cluster; 30 Doradus harbors R136, which, from \textit{HST} images (e.g., Meylan, 1993), is known to have the dense core and extended halo structure typical of a young globular cluster or YPC. Since the timescale for the formation of a YPC is comparable to the lifetime of a giant H\textsc{ii} region (Kennicutt & Chu 1988), it is highly likely that the cores of objects like 30 Doradus will be identified as YPCs when the surrounding OB associations have faded.

\textit{HST} observations of NGC 4038/9 (e.g., Whitmore & Schweizer 1995) show both spectacular populations of giant \(n\) regions and hundreds of YPCs. Evidence of an association between YPCs and 30 Dor GHRs is provided by a comparison of YPCs with multiwavelength emission in NGC 4038/9 by Zhang et al. (2001). They find that red clusters (age \(\leq 5\) Myr) are associated with radio continuum, CO, and infrared emission; that blue young clusters (3 \(\leq\) age \(\leq 16\) Myr) are correlated with H\textalpha\ and X-ray emission; and bright, older clusters (16 \(\leq\) age \(\leq 160\) Myr) are correlated with X-ray emission. They note that this is consistent with the cluster heating the dusty environment it formed in, then ionizing the surrounding gas, and finally expelling the surrounding material via stellar winds and supernovae.

In NGC 3256 Lira et al. (2002) observed diffuse X-ray emission, using the \textit{Chandra} X-ray Observatory, that spatially coincides with diffuse H\alpha\ emission, and they claim that this evidence that the X-ray gas is heated by a starburst (rather than an AGN). Additionally, most of their discrete X-ray sources are coincident with H\textsc{ii} knots; see Table 3 for correlations with our observations of diffuse emission. The potential sources generating the discrete X-ray emission include supernova remnants and X-ray binaries. This suggests the sources are in clusters with massive stars, which may be initially embedded in H\textsc{ii} regions in a manner consistent with the Zhang et al. picture.

This picture is echoed by Alonso-Herrero et al. (2002), who specifically look for a spatial correspondence between H\textsc{ii} regions and YPCs in NGC 3256 using NICMOS Pa\alpha\ and infrared images. They use evolutionary synthesis models to indicate that the \(\sim 8\%\) coincidence rate, compared with the number of H\textsc{ii} regions + star clusters, is due to evolution effects and their detection thresholds. That is, after 9 Myr the \(H\)-band luminosity, which is used to detect YPC, peaks while the H\alpha\ luminosity drops below their

| TABLE 2 |
| --- |
| **Dynamical Masses in NGC 3256** |

| Radius | Mass | Position of Radius |
| --- | --- | --- |
| (arcsec) | (kpc h\(^{-1}\)) | (10^{8} h\(^{-1}\) M\(_{\odot}\)) |
| 70 | 10 | 2.5 ± 0.5 At the edge of I-band envelope |
| 22 | 3 | 0.8 ± 0.2 At the outer edge of H\textsc{ii} ring |
| 13 | 2 | 0.5 ± 0.1 At the turnover peaks in optical velocity curve |

**Notes.**—The radius used in the mass calculation is given in both angular and linear units. The dynamical mass calculation is described in § 3.1.

3. DESIGNATIONS OF H\alpha\ EMISSION MEASUREMENTS PLUS DISCRETE X-RAY SOURCES

| H\alpha\ Emission | X-Ray Sources |
| --- | --- |
| Figure 1 | Feast & Robertson | Lipari et al. | Lira et al. |
| B1 | T | R1, R9 | 7, 6 |
| B2 | Y, Z | R2, R8, R4 | 10 |
| B3 | X | R5 | 11 |
| B4 | W | R15 | 9 |
| B5 | | R11, R10, R6 | (3 is just south) |
| B6 | S | R7 | 2 |
| B7 | | R19 | |

**Notes.**—See Fig. 1 for H\textsc{ii} region designations for our data. Note that our measurements do not precisely coincide with the H\textsc{ii} emission regions selected by Feast & Robertson 1978. Also Lipari et al. 2000 measure smaller H\alpha\ knots and do not account for all of the emission in our selected areas. We only include the discrete X-ray sources plotted in the figures of Lira et al. 2002. Besides the southern nucleus, X-ray sources 5 and 12 are missing from this table; our H\alpha\ spectra mapped in Fig. 2 suggest that 5 is associated with diffuse emission, while 12 occurs in an apparent gap in H\alpha\ emission.
detection limit. Since the $H$-band luminosity threshold allows detection of clusters from ages 0–100 Myr, more YPCs are detected than H II regions. Those H II regions without detected IR clusters probably harbor clusters that are obscured by dust in the manner of Galactic H II regions less than 5 Myr old. Alonso-Herrero et al. (2002) believe that they are only detecting spatial coincidences when the YPC have masses $\sim 10^6 M_\odot$ and ages less than 7 Myr.

At optical wavelengths Zepf et al. (1999) find about 1000 blue, compact clusters in the inner region of the NGC 3256 merger. Therefore, at an order-of-magnitude level, we can compare the number of clusters like R136 with an estimate of the specific frequency of GCs required if NGC 3256 is a merger of two galaxies.

To determine the number of R136-like clusters, we first select only those Zepf et al. clusters with $-0.55 < (B-I) < 0.5$. Bruzual & Charlot (1993) models generate unique ages between 3 and 7 Myr for clusters in this color range. Also, models by Schaerer & de Koter (1997 and papers listed therein) suggest O and B stars provide ionizing radiation for about 7 Myr, making these clusters comparable in age to the observed H II regions that might harbor them.

The observed absolute magnitudes ($M_B$) of these blue YPCs are calculated using $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$. The change in the $M_B$ of R136 ($-12.6$; Kennicutt & Chu 1988) is also calculated for the 3 to 7 Myr age range according to the Bruzual & Charlot (1993) models. Examining the difference between the observed magnitude of a cluster and the magnitude predicted for R136 at same age as the cluster, indicates that 17 out of 196 of the bluest clusters have luminosities, and hence masses, greater than R136. The total mass in the 17 clusters is equivalent to about 45 times the mass in R136 ($M_{R136}$). (The Alonso-Herrero et al. 2002 clusters that are coincident with H II regions probably have ages between 3–7 Myr and masses $\sim 10^6 M_\odot$. At least 18 coincidences occur in the 19.5 arcsec$^2$ field-of-view of NIC2. Scaling this area to match the 36 arcsec$^2$ area of the PC chip predicts the existence of 60 IR clusters with R136-like masses, which is comparable to our estimate of 45.) Extrapolating to the $\sim 1000$ YPCs detected by Zepf et al. (1999) suggests that there are roughly 100 YPCs with masses greater than R136, or a total of 225 $M_{R136}$ clusters.

Thus, we estimate the existence of 100–200 massive YPCs; 100 YPCs if the masses are distributed amongst clusters in a manner similar to this sample and approaching 200 YPCs if more of the clusters are about 1 $M_{R136}$. This is a conservative estimate, since only a limited field of view has been studied. Additionally, our threshold of $B-I < 0.5$ eliminates blue clusters reddened by intervening dust, and we note that all 17 clusters are situated in the less dusty east section of the disk.

An alternative YPC estimate uses H$\alpha$ photometry and also suggests that more than 200 R136-like clusters could form over the lifetime of the galaxy-galaxy interaction. Five H II complexes in Table 1 have fluxes above $1.5 \times 10^{40}$ ergs s$^{-1}$, giving a total of 85 30 Dor GHRs, not including those that might exist in the obscured southern nucleus. (This is consistent with Alonso-Herrero et al. 2002, who detect at least 50 30 Dor GHRs in the field of view of NIC2, which includes only B1, B5, part of B6, and B8. Our remaining H II complexes contribute 67% of the H$\alpha$ luminosity due to 30 Dor GHRs. This implies about 35 30 Dor GHRs were not imaged by NIC2.) All the Zepf et al. clusters but one project onto the sky in the vicinity of the three 30 Dor GHRs regions in the 7 kpc $\times$ 7 kpc field of view that they analyzed. The number of bright, blue R136-like clusters associated with the 30 Dor GHRs suggests that 20%–50% of these 30 Dor GHRs may currently cradle YPCs. Notably, Alonso-Herrero et al. (2002) claim about 55% of their high-luminosity H II regions have an IR cluster counterpart.

To estimate the total number of YPCs that might form from 30 Dor GHRs over the era of the current interaction stage, we consider the rate of 30 Dor GHRs formation in NGC 3256. Using a lifetime of 7 Myr gives a current rate of 12 Myr$^{-1}$ (compared with less than 0.2 Myr$^{-1}$ for a typical Sc galaxy with $M_B = -19.5$ Kennicutt & Chu 1988). This enhanced rate could be maintained for longer than the age of the nuclear starburst (between 10 and 27 Myr; Doyon, Joseph, & Wright 1994 and Rigopoulou et al. 1996). However, the numerical merger simulations of Mihos & Hernquist 1994, in which each parent galaxy has a bulge, suggest that this rate has probably not been continuous. The global star formation rate of each parent galaxy increases by only a few percent until the galaxy cores coalesce, and then the star formation rate increases dramatically.

Assuming that the cores are now about to merge, the time from pericenter through to coalescence is about 50 model units, corresponding to about 500 h$^{-1}$ Myr in NGC 3256 (see Paper II). The peak of the star formation extends over about 4 model units, or about 40 h$^{-1}$ Myr in NGC 3256. If we are now observing the peak star formation rate, then this time interval generates at least 640 30 Dor GHRs (for $h = 0.75$). The formation rate for the previous 400 h$^{-1}$ Myr is about 7% of the peak rate value. Hence, another 250 H II regions probably formed between the time of pericenter separation and the observed enhanced star formation epoch. If 20%–50% of the 30 Dor GHRs harbor R136-like clusters, then we might expect at least 200–400 YPCs to form over the lifetime of the interaction.

Although there is some controversy about the relationship between the YPC mass function and the GC mass function (see Fritz–von Alvensleben 2001 and papers therein), we believe that the R136-like clusters in the Zepf et al. data will acquire GC colors and luminosities over several gigayears. It is difficult to estimate how many of the R136-like clusters would survive the evolution of the NGC 3256 globular cluster system (GCS) over the next several gigayears. However, if the current power-law luminosity function of the YPC system (Zepf et al. 1999) transforms to the log-normal distribution of an older GCS mainly via evaporation (due to internal relaxation), then the loss of mass occurs mainly among clusters less massive than those in the median mass bin (Fall & Zhang 2002). Since the mass of R136 corresponds to the median bin values, we expect that these couple of hundred YPCs may survive.

If typical ellipticals form via the merging of spirals, the number of new massive clusters formed in the merger needs to be at least comparable to the number of globular clusters originally associated with the spirals (e.g., Ashman & Zepf 1993). Hence, we now estimate the original number of GCs and compare it with the number of YPCs in NGC 3256. To get an order-of-magnitude estimate of the number of GCs associated with NGC 3256’s parent systems, we arbitrarily assume that the parent galaxies have similar bulge/disk ratios to M31 and compare the dynamical mass ($\sim 3 \times 10^{10}$...
h^{-1} M_\odot) within the radius of the I-band envelope of NGC 3256 with the dynamical mass of M 31 (3 \times 10^{11} M_\odot) within the 20 kpc radius of its globular cluster system (Huchra 1993). Since M31 has about 400 confirmed GCs (Fusi Pecci et al. 1993), scaling by the ratio of dynamical masses suggests that the original number of GCs belonging to the two-parent system was roughly 40–80. The larger value uses the Feast & Robertson (1978) inclination and position angle (see § 3.1). As a check we use the specific frequency per unit mass for disk galaxies (2.2 clusters times 10^9 M_\odot^{-1}; Zepf & Ashman 1993), which gives 66 GCs.

In summary, since ellipticals have typically more than twice as many GCs per unit mass as spirals (e.g., Ashman & Zepf 1993), we need at least as many GCs to form in the merger as originally existed in the parent system. If NGC 3256 is the result of the interaction of two similar disk galaxies, as indicated by its two optical tails, then the number of GCs required would be less than 100. Extrapolating from the fraction of the bluest YPCs observed in NGC 3256, roughly 100–200 YPCs are expected to have masses equal to or greater than R136. (Using H_\alpha photometry and numerical models suggests 200–400 R136-like clusters form.) These should fade to GC luminosities over several gigayears, and many are expected to survive destruction since it is the lower mass clusters that evaporate. Hence, the observed YPCs appear numerous enough to populate the GCS of the emerging galaxy, such that its specific frequency will be consistent with that observed in typical elliptical galaxies.

Additionally, the bluest, massive YPCs are located in the vicinity of observed 30 Dor GHRs, contributing to the notion that some fraction of 30 Dor GHRs do cradle massive YPCs, as 30 Dor harbors R136. If interactions induce the formation of 30 Dor GHRs, the observed luminosities indicate that almost 900 30 Dor GHRs would form in NGC 3256 throughout its merger epoch. In order for 30 Dor GHRs to be considered GC progenitors, the specific frequency argument only requires that about 10% of these harbor YPCs that survive several gigayears and have masses \geq M_{R136}.

4. CONCLUSIONS

An approach outlined in our introduction, which would be fruitful for assessing whether giant H II regions may be globular cluster birthplaces, uses hydrodynamic modeling in order to see whether the kinematics of the H II regions at various interaction and merger stages is consistent with the final spatial distribution of GCs in elliptical (i.e., merger remnant) galaxies. This approach should be applied to a sample of galaxies spanning the interaction stages that lead to a merger remnant. It requires a comparison of observed H II region positions and velocities throughout the merger sequence with the statistical position and velocity distributions of condensations of stellar and gas particles seen in simulations that generate elliptical-like merger remnants (e.g., Mihos & Hernquist 1996). At every interaction stage the behavior of the observed progenitor candidate should be similar to that of the condensations in the model. If this picture is correct, both the observed and numerical sequence should produce a GCS that is consistent with GCSs observed around elliptical galaxies.

Another approach compares the observed specific frequency of GCs in typical ellipticals with an estimate of the number of GCs formed as two similar disk galaxies interact and coalesce to form an elliptical merger remnant. Since ellipticals have typically twice as many GCs per unit mass as spirals, at least as many GCs need to be created in the merger process as originally existed in the sum of the two parent galaxies (Ashman & Zepf 1993). The argument is that tidal disturbances provide a mechanism for enhancing star formation and hence generate giant H II regions in the disk of the emerging elliptical. On theoretical grounds interactions are expected to lead to enhanced H II region formation (e.g., Larson 1987), and observations demonstrate that giant H II region populations are enhanced at various stages of the interaction-through-merger sequence (e.g., NGC 4038/9, NGC 5426). These ionized complexes in turn could be YPCs. (Support that YPCs are associated with H II regions is provided by their correlation in NGC 4038/9: Zhang et al. 2001.) Massive YPCs are expected to survive evaporation from the GC system of the emerging elliptical, and we believe that these YPCs will fade over several gigayears, such that they would be recognized as GCs. The optical data on NGC 3256 presented in this paper allow us to explore this approach.

To get an order-of-magnitude estimate of the number of GCs associated with NGC 3256’s parent systems, we arbitrarily assumed that the parent galaxies have similar bulge/disk ratios to M31. Using M31’s number of GCs per unit mass suggests the original number of GCs belonging to the two-parent system was roughly 40–80. Thus, over NGC 3256’s merger period about 100 YPCs must form and survive if the above scenario is correct.

Although NGC 3256 has relatively few (seven) H II complexes compared with some other interacting systems, five of these regions are comparable in flux to about 85 30 Dor giant H II regions (30 Dor GHRs; each with an H_\alpha flux of 1.5 \times 10^{40} \text{ergs} \text{s}^{-1}). Given that these 30 Dor GHRs formed within the previous 7 Myr, this merging system currently has a giant H II region formation rate 60 times that observed in an Sc galaxy with M_B = −19.5 (Kennicutt & Chu 1988). The 30 Dor nebula contains the YPC R136 within NGC 2070 (Meylan 1993), and the formation timescale for YPCs is comparable to the lifetime of a giant H II region (Kennicutt & Chu 1988). Also, clusters as massive as R136 are expected to survive evaporation due to internal relaxation (S. M. Fall 2000, private communication) and hence become part of the remnant elliptical’s GCS. Therefore, we used this flux as a minimum criterion for identifying which H II regions are potential birthplaces of YPCs (Kennicutt & Chu 1988).

An order-of-magnitude estimate of the total number of YPCs created throughout the merger sequence experienced by NGC 3256’s parent galaxies was determined in two ways. For one estimate we determined that about 1/10 of the ~200 bluest clusters observed in the inner region of NGC 3256 by Zepf et al. (1999) have luminosities, and hence masses, greater than R136. Extrapolating to the ~1000 detected clusters implies that 100–200 YPCs exist. The alternative estimate used H_\alpha photometry and the variation in star formation rate over the interaction-through-merger timescale, calculated using existing numerical simulations (Mihos & Hernquist 1994). These indicated about 900 30 Dor GHRs formed since the last pericenter approach of the
parent galaxies, yielding 200–400 YPCs if 20%–50% of 30 Dor GHRs have R136-like clusters. We expect clusters this massive to survive destruction.

If NGC 3256 is typical of the merging systems that form globular clusters and if about 10% of the 30 Dor GHRs harbor clusters that survive several gigayears, this would be sufficient to explain the high specific frequencies of clusters in ellipticals.

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