CLUSTERS IN THE LUMINOUS GIANT H II REGIONS IN M101

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ABSTRACT

We have obtained HST WFPC2 observations of three very luminous but morphologically different giant H II regions (GHRs) in M101, NGC 5461, NGC 5462, and NGC 5471, in order to study cluster formation in GHRs. Images obtained in the F547M and F675W bands are used to identify cluster candidates and for photometric measurements, and images in the F656N band are used to show ionized interstellar gas. The measured colors and magnitudes are compared with the evolutionary tracks generated by the Starburst99 and Bruzual & Charlot population synthesis models to determine the ages and masses of the cluster candidates that are more luminous than $M_{F547M} = -9.0$. The brightest clusters detected in the PC images are measured and found to have effective radii of $0.7-2.9$ pc. NGC 5461 is dominated by a very luminous core and has been suggested to host a super–star cluster (SSC). Our observations show that it contains three R136-class clusters superposed on a bright stellar background in a small region. This tight group of clusters may dynamically evolve into an SSC in the future, and may appear unresolved and be identified as an SSC at large distances, but at present NGC 5461 contains no SSCs. NGC 5462 consists of loosely distributed H II regions and clusters without a prominent core. It has the largest number of cluster candidates among the three GHRs studied, but most of them are faint and older than 10 Myr. NGC 5471 has multiple bright H II regions and contains a large number of faint clusters younger than 5 Myr. Two of the clusters in NGC 5471 are older than R136, but just as luminous; they may be the most massive clusters in the three GHRs studied. The fraction of stars formed in massive clusters has been estimated from the clusters’ contribution to the total stellar continuum emission and from a comparison between the ionizing power of the clusters and the ionizing requirement of the associated H II regions. Both estimates show that $\leq 50\%$ of massive stars are formed in massive clusters; consequently, the H$\alpha$ luminosity of an H II region does not provide a sufficient condition for the existence of SSCs. The cluster luminosity functions (LFs) of the three GHRs show different slopes. NGC 5462 has the steepest cluster LF and the most loosely distributed interstellar gas, qualitatively consistent with the hypothesis that massive clusters are formed in high-pressure interstellar environments. The combined cluster LF of the three GHRs has a slope similar to the universal cluster LFs seen in starburst galaxies and nonstarburst spiral galaxies.

Subject headings: galaxies: individual (M101) — galaxies: star clusters — H II regions — stars: formation

1. INTRODUCTION

Giant H II regions (GHRs) are sites of intense massive star formation. Their H$\alpha$ luminosities, $10^{39}-10^{41}$ ergs s$^{-1}$ (Kennicutt 1984), require an ionizing power equivalent to that of 24–2400 O5 V stars (Schaerer & de Koter 1997). With such high concentrations of massive stars, GHRs provide an excellent laboratory to study the modes of massive star formation, and in particular to probe whether they are birthplaces of globular clusters (Kennicutt & Chu 1988).

In the two nearest GHRs, 30 Dor in the Large Magellanic Cloud (LMC) and NGC 604 in M33, where stellar contents are well resolved, two distinct types of stellar groupings have been observed: 30 Dor is dominated by one central massive cluster R136 (Hunter et al. 1995; Walborn & Blades 1997), while NGC 604 contains multiple OB associations spreading over a large area (Hunter et al. 1996). Evidently, not all GHRs contain massive compact clusters; what physical environments give rise to the various cluster morphologies is currently under investigation.

One obvious way to elucidate this issue is to carry out detailed examinations of relatively nearby clusters and their environments. Maiz-Apellániz (2001) studied 27 nearby (<5 Mpc) clusters of varying morphological types, primarily classifying clusters based on their core and halo sizes. He suggests that compactness of clusters is predominantly related to the central density of the progenitor giant molecular cloud, i.e., extremely high pressure environments may be required to form massive compact clusters. However, this scenario has not been observationally tested; we do not know the pressures and densities of the giant molecular cloud in which optically visible clusters were formed. Examining clusters in a range of present-day environments may help us gain insight into their properties and relationship to their natal interstellar medium.

Of all massive compact clusters, the most impressive ones are the super–star clusters (SSCs) with masses of $10^5-10^6 M_\odot$. SSCs are frequently observed in galaxy mergers and starburst galaxies (Whitmore 2003 and references therein), and they are believed to be preferentially formed in high-pressure interstellar...
conditions (e.g., Elmegreen & Efremov 1997). However, some GHRs in noninteracting, late-type spiral galaxies may also host SSCs, especially those GHRs that are several times as luminous as 30 Dor and require ionizing powers rivaling those of young SSCs (e.g., Luridiana & Peimbert 2001). It is thus intriguing to examine the cluster content of such GHRs and investigate whether these relatively quiescent environments can also produce SSCs.

The giant spiral galaxy M101 contains a large number of very luminous GHRs whose stellar content can be resolved and studied with Hubble Space Telescope (HST) images. We have therefore obtained HST observations of three M101 GHRs with different morphologies and galactic locations: NGC 5461, NGC 5462, and NGC 5471. The locations of these GHRs in M101 are marked on a Second Palomar Observatory Sky Survey (POSS-II) red image in Figure 1. The properties of these GHRs are summarized in Table 1; for comparison, 30 Dor is also included in this table. We have used the HST continuum and Hα images of these three GHRs to carry out a detailed photometric study of their clusters. This paper reports our observations (§ 2) and methodology (§ 3), describes the cluster content in each GHR (§ 4), discusses cluster properties and their implications in studying massive star formation and cluster formation (§ 5), and summarizes our results (§ 6).

2. OBSERVATIONS AND DATA REDUCTION

The HST WFPC2 images of the GHRs NGC 5461, NGC 5462, and NGC 5471 were obtained for the Cycle 6 program GO-6829. The observations were made through the continuum filters F547M (Strömgren y) and F675W (WFPC2 R), and the Hα filter F656N (for filter characteristics, see Biretta et al. 1996). Multiple exposures in each filter were made with a GHR centered on a Wide Field Camera (WFC) for photometric measurements. Two short exposures in F547M with the GHR centered on the Planetary Camera (PC) were also made for cluster size measurements. The observations are listed in Table 2.

We received the HST pipeline processed WFPC2 images and then reduced them further with the IRAF and STSDAS routines. All images were corrected for the intensity- and position-dependent charge transfer efficiency by applying a linear ramp with a correction factor chosen according to the average counts of the sky background (Holtzman et al. 1995). Images in each filter were then combined to remove cosmic rays and to produce a total-exposure map. To better illustrate the spatial correlation between the stars/cluster and the ionized gas, we have produced color images of the three GHRs using a customized IDL routine. The individual F547M, F675W, and Hα images were mapped to the colors blue, green, and red, respectively. These images were transformed to a logarithmic scale, and the maximum and minimum flux values for each filter were chosen in order to maximize the dynamic range of the image while also creating a relatively black background. The color images of NGC 5461, NGC 5462, and NGC 5471 are shown in Figures 2–4, where the ionized gas appears red and most stars blue. The individual F547M, F675W, and Hα images of NGC 5461, NGC 5462 and NGC 5471 are presented in Figures 5–7, respectively.

Aperture photometry was carried out using the IRAF task apphot for the F547M and F675W images. Owing to the small number of identifiable candidate sources and the complex blending and irregular background in some regions, we manually selected compact sources with obvious peaks as candidate clusters in the three GHRs. The candidate clusters in the three GHRs are marked in Figures 5–7. The apparent magnitudes, $m_{F547M}$ and $m_{F675W}$, were measured with the WFC images using a source aperture of radius 2 pixels ($0.2$ arcsec) and an annular background aperture of radii $6–11$ pixels. For clusters with neighboring clusters within $\leq 0.3$ arcsec, such as clusters 8, 9, and 10 in NGC 5461 and 1 and 2 in NGC 5471, the photometry was measured with a $0.15$ radius source aperture using both the WFC and PC images. The corrections from the $0.15$ radius aperture to the $0.2$-radius aperture are determined by measuring isolated resolved and unresolved sources in each image, and are in the range of $-0.2$ to $-0.3$ mag. The fluxes of these clusters will be overestimated from the WFC images owing to the inclusion of neighbor’s light, and the errors are larger for the fainter clusters. For example, the error in the $m_{F675W}$ of NGC 5461-9 may be as large as $-0.4$ mag, which is estimated by comparing its $m_{F547M}$ measured from the PC and WFC images.

### Table 1

| Property | NGC 5461 | NGC 5462 | NGC 5471 | 30 Dor |
|----------|----------|----------|----------|--------|
| Angular size (arcsec) | $40 \times 25$ | $48 \times 33$ | $17 \times 17$ | $1200 \times 1200$ |
| Linear size (pc) | $1400 \times 875$ | $1680 \times 1150$ | $600 \times 600$ | $290 \times 290$ |
| $L_{H\alpha}$ (ergs s$^{-1}$) | $2.7 \times 10^{40}$ | $1.3 \times 10^{40}$ | $2.2 \times 10^{40}$ | $3.9 \times 10^{39}$ |
| Location | In spiral arm | In spiral arm | Outlier | Above one end of the LMC bar |
| Ho morphology | One dominant core with filaments and small cores around | Weak cores with long filaments and loops extending out | Multiple cores with filaments around | One core with bright loops and filaments around |

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*a* We adopted the distances of 7.2 Mpc to M101 (Stetson et al. 1998) and 50 kpc to the LMC (Feast 1999).

*b* The $L_{H\alpha}$ of NGC 5461, NGC 5462, and NGC 5471 are measured using HST WFPC2 Hα images in this study, and the $L_{H\alpha}$ of 30 Dor is adopted from Kennicutt & Hodge (1986). Note that these $L_{H\alpha}$ are not corrected for extinction.
## Table of Observations

| Object         | Observation Date | Filter | Camera | Exposure Time (s) |
|----------------|------------------|--------|--------|-------------------|
| NGC 5461       | 1999 Mar 24      | F547M  | WF2    | 600 (2), 100 (2), 20 (1) |
|                |                  | F547M  | PC1    | 20 (2)            |
|                |                  | F675W  | WF2    | 400 (2), 50 (2), 10 (1) |
|                | 1999 Mar 23      | F656N  | WF2    | 600 (2), 160 (1)  |
| NGC 5462       | 2000 Feb 1       | F547M  | WF2    | 600 (2), 100 (2), 20 (1) |
|                |                  | F547M  | PC1    | 20 (2)            |
|                |                  | F675W  | WF2    | 400 (2), 50 (2), 10 (1) |
|                |                  | F656N  | WF2    | 600 (2), 160 (1)  |
| NGC 5471       | 1997 Nov 1       | F547M  | WF3    | 600 (2), 100 (2), 20 (1) |
|                |                  | F547M  | PC1    | 20 (2)            |
|                |                  | F675W  | WF3    | 400 (2), 50 (2), 10 (1) |
|                |                  | F656N  | WF3    | 600 (2), 180 (1)  |

* Numbers in parentheses indicate the number of exposures.

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*Fig. 2.—Color composite of HST WFPC2 images of NGC 5461, with F547M in blue, F675W in green, and Hα in red. North is up, and east to the left. The field of view is $45'' \times 45''$, or 1.6 kpc $\times$ 1.6 kpc.*
We have derived the magnitudes in the VEGAMAG system. The errors in \(m_{F547M}\) given by \textit{apphot} are \(\sim 0.01\) mag for \(m_{F547M} \leq 20\), and rise to \(0.02-0.03\) mag for \(m_{F547M} = 20-21\). The errors in \(m_{F675W}\) are generally larger, with most of them \(\leq 0.02\) mag but some as high as 0.04 mag. These formal errors are derived from the flux variations in the background annulus used in the photometric measurements. In regions with bright irregular backgrounds, using different background apertures may produce different photometric results and the uncertainties in photometry will be larger than the formal errors given by \textit{apphot}. We have taken these uncertainties into account and estimated realistic errors.

The bright irregular sky background is attributed to both stars and nebulosity. The extended distribution of unresolved stars, similar to the “star clouds” defined by Lucke & Hodge (1970) for OB associations in the LMC, raises the background in both the F547M and F675W images. We find that using different annular sky backgrounds results in uncertainties of \(\sim 0.03-0.05\) mag in \(m_{F547M}\) for sources near modest star clouds, \(\sim 0.1\) mag for sources surrounded by bright star clouds, and up to \(\sim 0.2\) mag for faint sources near bright star clouds. The stellar background does not affect the \((m_{F547M} - m_{F675W})\) color as much because the variations in \(m_{F547M}\) and \(m_{F675W}\) are correlated. The bright nebular background, on the other hand, contributes uncertainties only to \(m_{F675W}\) and hence affects the color. The uncertainties in the \((m_{F547M} - m_{F675W})\) color are \(\sim 0.05-0.06\) mag for most sources near nebulosities, and up to \(\sim 0.16\) mag for faint stellar sources near bright nebulosity.

To reduce the uncertainties introduced by nebular contamination in the F675W images, we have produced H\(\alpha\)-free F675W images by subtracting scaled H\(\alpha\) images from the F675W images. The H\(\alpha\)-subtracted F675W images of the three GHRs are also presented in Figures 5–7. Aperture photometry has been carried out for the H\(\alpha\)-subtracted F675W images, and the apparent magnitude is designated as \(m_{F675W}'\). The uncertainties in the \((m_{F547M} - m_{F675W}')\) color with different annular sky backgrounds are generally larger, with most of them \(\leq 0.02\) mag but some as high as 0.04 mag. These formal errors are derived from the flux variations in the background annulus used in the photometric measurements. In regions with bright irregular backgrounds, using different background apertures may produce different photometric results and the uncertainties in photometry will be larger than the formal errors given by \textit{apphot}. We have taken these uncertainties into account and estimated realistic errors.

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backgrounds are reduced to $\sim 0.02$–$0.05$ mag for most candidate cluster sources near nebulosities.

Our $0''2$ radius source aperture does not include all the light from a cluster. The correction from a $0''2$ radius aperture to a $0''5$ radius aperture, which includes $\sim 95\%$ of the light of a point source (Holtzman et al. 1995), is $\sim -0.20 \pm 0.06$ mag for unresolved sources and larger for resolved sources. As the cluster candidates are resolved to different extents, the aperture corrections are in the range of $-0.2$ to $-0.3$ mag but difficult to determine exactly. We have chosen not to apply aperture corrections; therefore, our photometric measurements are systematically fainter by $0.2$–$0.3$ mag, but the analysis and conclusions of this paper are not sensitive to such small offsets that incur on the magnitudes and colors of the clusters.

The photometric results of NGC 5461, NGC 5462, and NGC 5471 are presented in Tables 3–5 and are plotted in the color-magnitude diagram (CMD) of $M_{F547M}$ versus $(M_{F547M} - M_{F675W})$ in Figures 8, 9, and 10, respectively. For clusters with close neighbors, their $M_{F547M}$ measured from the PC images and their $(M_{F547M} - M_{F675W})$ measured from the WFC images are used in the CMD. These absolute magnitudes are derived using a distance modulus of $(m - M) = 29.3$ (Stetson et al. 1998). The Galactic foreground extinction toward M101, $E(B - V) = 0.01$ (Schlegel et al. 1998), is corrected, although its effect is negligible. The internal extinction from M101 is not individually corrected for, given that it is highly variable and the measurements are only available for certain parts of the GHRs.

3. METHODOLOGY

The observed magnitudes and colors of the clusters can be used to determine their ages and masses through comparisons with those predicted by population synthesis models (e.g., Elson & Fall 1985; Bruzual & Charlot 1993; Bruzual & Charlot 2003; Leitherer et al. 1999). Below we describe the synthetic photometry derived from models and how we use it.
to estimate the properties of clusters. We have also used the Larsen (1999) method to measure the sizes of clusters from their surface brightness profiles. The procedures of cluster size measurements are outlined at the end of the section.

3.1. Synthetic Photometry

We have used the Starburst99 models (Leitherer et al. 1999) and the Bruzual & Charlot (2003, hereafter BC03) models to generate synthetic photometry for comparison with observations of our cluster candidates in GHRs. We have adopted a Salpeter initial mass function (IMF) with lower and upper mass limits of 1 and 100 $M_{\odot}$, which are commonly used in population synthesis models for star-forming and starburst regions. The luminosity, colors, and evolution of a cluster depend on its metallicity. To select appropriate models, we have used the observed oxygen abundances of the GHRs to assess their metallicities, because clusters and their surrounding GHRs are expected to have the same abundances and the oxygen abundances are well determined. Oxygen abundances of NGC 5461 and NGC 5462, relative to the solar value, have been measured to be 0.6–0.9, while that of NGC 5471 is ~0.25 (e.g., Evans 1986; Scowen et al. 1992; Pilyugin 2001; Luridiana et al. 2002). Therefore, we adopt the 1 Z$_{\odot}$ model for NGC 5461 and NGC 5462, and the 0.2 Z$_{\odot}$ model for NGC 5471.

The F547M and F675W filters we used are not included in the default filter systems of Leitherer et al. (1999) or BC03 for which synthetic photometry is readily available; thus, customized procedures are needed to derive synthetic $M_{F547M}$ and $M_{F675W}$ bands.

Fig. 5.—HST WFPC2 images of the main body of NGC 5461 in (a) F547M, (b) F675W, (c) Hα, (d) Hα-subtracted F675W, (e) continuum-subtracted Hα, and (f) F547M bands. Note that this field of view is smaller than that shown in Fig. 2. The Hα images (c) and (e) are presented in different stretches to show bright and faint features, and similarly the F547M images (a) and (f) to show bright and faint stars/clusters. The two brightest H α regions from Hodge et al. (1990) are marked in (e), and cluster candidates are marked in (f).
As the first step, we use Starburst99 version 4.0 to
generate integrated stellar spectra for a simple stellar popula-
tion (SSP; i.e., a single-age and single-abundance group of
stars) of ages from 0 to 30 Myr at 1 Myr intervals and from 30
to 150 Myr at 3 Myr intervals. This step is not necessary for the
BC03 models, as integrated spectra for an SSP are available for
most of these age intervals. These model spectra are those
without nebular line and continuum emission because the clus-
ters are generally well resolved from the superposed extended
nebular emission and the background-subtraction in
apphot adequately removes the extended nebular emission. The syn-
thetic spectra from Leitherer et al. (1999) and BC03 are then
convolved with filter transmission curves, using the IRAF/
STSDAS task calcphot, to calculate the synthetic $M_{F547M}$ and
$M_{F675W}$. We have produced synthetic photometry for SSPs
with metallicities of 0.2 and 1 $Z_\odot$, and generated evolutionary
tracks in the CMDs in Figures 8–10 for comparisons with ob-
servations of NGC 5461, NGC 5462, and NGC 5471, respect-
ively. The differences in the two sets of evolutionary tracks reflect the differences between the Geneva and Padova stellar
evolution models used by Leitherer et al. (1999) and BC03,
respectively. However, the effects of these differences are small
compared to the uncertainties in the cluster mass estimates.

We use the R136 cluster at the core of 30 Dor as a reference
point, because it is an archetypical populous blue cluster and
possibly a young globular cluster. The R136 cluster is ~3 Myr
old (Hunter et al. 1995; Walborn & Blades 1997). Its spatially
resolved photometry in the $V$ band has been measured and the absolute visual magnitude within a radius of 7 pc is $M_V =
-11.1$ (Moffat et al. 1985). This $V$ band magnitude is adopted
directly because its central wavelength is similar to that of
F547M and the 7 pc radius aperture matches that used in the

![HST WFPC2 images of the main body of NGC 5462, displayed in a format identical to that of Fig. 5. Note that this field of view is smaller than that shown in Fig. 3. The three brightest H II regions from Hodge et al. (1990) are marked in (e), and cluster candidates are marked in (f).]
photometric measurements of M101 clusters. The \((M_{F547M} - M_{F675W})\) color of R136 is not available, so we use the synthetic color generated by Starburst99 for a 3 Myr old cluster with \(Z = 0.2 - 0.4 Z_\odot\). As no extinction correction has been applied to the M101 clusters, we have reddened the synthetic color of R136 with its visual extinction \(A_V = 1.2\) (Moffat et al. 1985) and marked both the dereddened and reddened R136 in the CMDs in Figures 8–10.

3.2. Assessing Masses and Ages of Clusters

The mass and age of a cluster can be assessed by comparing its magnitudes and colors to model predictions if photometric data are available in three passbands. For a young cluster, it is important to include a \(U\) band or a \(B\) band because the spectral energy distribution of young massive stars peaks in the ultraviolet wavelengths. Unfortunately, only F547M and F675W photometry is available for the clusters in M101 GHRs, and these two bands are not as sensitive to the young massive stars as the \(U\) and \(B\) bands. We cannot determine unambiguously the cluster masses and ages by comparing the photometric measurements with the evolutionary tracks of SSPs in the CMDs. However, we may use the interstellar environment as an independent diagnostic of the cluster age, as the interstellar medium around a cluster evolves as a result of stellar energy feedback.

At ages of less than 5 Myr, a cluster has the highest ionizing power, and hence will be in a dense, luminous H \(\Pi\) region. At ages 5–10 Myr, the fast stellar winds and supernova explosions from a cluster have swept up the ambient interstellar medium into a supershell with a visible cavity around the cluster. At ages greater than 10 Myr, a cluster loses its ionizing power and has dispersed its ambient gas, so it will be surrounded only by diffuse gas with low surface brightness. We have compared the \(H\alpha\) images with the continuum images to examine the interstellar

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**Fig. 7.**—HST WFPC2 images of NGC 5471, displayed in a format identical to that of Fig. 5. Note that this field of view is smaller than that shown in Fig. 4. The five brightest components from Skillman (1985) are marked in (e), and cluster candidates are marked in (f).
environment of the clusters and to assess the approximate ages of the clusters. In Figures 8–10 we mark circles around the clusters that are coincident with compact, luminous H II regions and dashed circles around the clusters that are in supershells, indicating that their ages are less than 5 and 5–10 Myr, respectively. The unmarked clusters, not surrounded by bright Hα emission, are older than 10 Myr, but their exact ages are poorly constrained.

With a rough estimate of the cluster age, it is then possible to compare the location of a cluster in the CMD with the synthetic evolutionary tracks of clusters to determine the cluster mass. The photometric measurements of the clusters have not been corrected for the extinction within M101; thus, using these reddened magnitudes would underestimate cluster masses. To illustrate the effect of extinction and to make a rough correction, we take the visual extinctions of the GHRs determined

### Table 3

| ID | (J2000.0) | (J2000.0) | $M_{F547M}$ | $M_{F547M} - M_{F675W}$ | $M_{F547M} - M_{F675W'}$ |
|----|-----------|-----------|--------------|-------------------|-------------------|
| 1  | 14 03 39.84 | 54 18 56.2 | -9.35 ± 0.01 | 0.45 ± 0.05 | 0.23 ± 0.02 |
| 2  | 14 03 39.91 | 54 18 56.2 | -8.19 ± 0.05 | 1.26 ± 0.06 | 0.55 ± 0.06 |
| 3  | 14 03 40.52 | 54 18 58.8 | -8.97 ± 0.01 | 0.17 ± 0.03 | 0.16 ± 0.02 |
| 4  | 14 03 40.54 | 54 18 59.2 | -8.11 ± 0.03 | 0.14 ± 0.08 | 0.11 ± 0.04 |
| 5  | 14 03 40.98 | 54 19 02.1 | -8.25 ± 0.02 | 0.11 ± 0.06 | 0.09 ± 0.03 |
| 6  | 14 03 41.15 | 54 19 04.5 | -9.61 ± 0.03 | 0.21 ± 0.09 | 0.10 ± 0.04 |
| 7  | 14 03 41.22 | 54 18 57.0 | -8.01 ± 0.02 | 0.17 ± 0.02 | 0.13 ± 0.02 |
| 8a | 14 03 41.36 | 54 19 03.7 | -10.40 ± 0.10 | 0.59 ± 0.13 | 0.36 ± 0.10 |
| 9a | 14 03 41.40 | 54 19 03.8 | -10.17 ± 0.12 | 0.39 ± 0.16 | 0.24 ± 0.14 |
| 10 | 14 03 41.42 | 54 19 04.0 | -10.81 ± 0.06 | 0.27 ± 0.09 | 0.22 ± 0.07 |
| 11 | 14 03 41.58 | 54 19 04.0 | -9.27 ± 0.05 | 1.37 ± 0.05 | 0.58 ± 0.05 |
| 12 | 14 03 41.58 | 54 19 07.8 | -8.37 ± 0.01 | 0.38 ± 0.03 | 0.38 ± 0.02 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

### Table 4

| ID | (J2000.0) | (J2000.0) | $M_{F547M}$ | $M_{F547M} - M_{F675W}$ | $M_{F547M} - M_{F675W'}$ |
|----|-----------|-----------|--------------|-------------------|-------------------|
| 1  | 14 03 51.80 | 54 21 52.6 | -8.83 ± 0.04 | 0.32 ± 0.05 | 0.16 ± 0.04 |
| 2  | 14 03 51.83 | 54 21 46.2 | -8.08 ± 0.01 | 0.31 ± 0.02 | 0.27 ± 0.02 |
| 3  | 14 03 51.98 | 54 21 46.7 | -8.64 ± 0.01 | 0.36 ± 0.03 | 0.33 ± 0.02 |
| 4  | 14 03 52.07 | 54 21 49.1 | -8.32 ± 0.01 | 0.46 ± 0.01 | 0.43 ± 0.01 |
| 5  | 14 03 52.38 | 54 21 49.5 | -8.33 ± 0.02 | 0.20 ± 0.03 | 0.15 ± 0.03 |
| 6  | 14 03 52.41 | 54 21 49.1 | -9.56 ± 0.01 | 0.43 ± 0.01 | 0.40 ± 0.01 |
| 7  | 14 03 52.42 | 54 21 49.4 | -8.16 ± 0.05 | 0.47 ± 0.05 | 0.44 ± 0.05 |
| 8  | 14 03 52.43 | 54 21 50.0 | -8.86 ± 0.02 | 0.30 ± 0.02 | 0.28 ± 0.02 |
| 9  | 14 03 52.84 | 54 21 54.5 | -8.05 ± 0.02 | 0.14 ± 0.03 | 0.12 ± 0.03 |
| 10 | 14 03 52.86 | 54 21 59.3 | -8.13 ± 0.02 | 0.63 ± 0.02 | 0.59 ± 0.02 |
| 11 | 14 03 52.95 | 54 21 54.2 | -8.55 ± 0.01 | 0.65 ± 0.02 | 0.52 ± 0.02 |
| 12 | 14 03 52.96 | 54 22 06.4 | -8.75 ± 0.03 | 1.41 ± 0.03 | 0.37 ± 0.03 |
| 13 | 14 03 53.01 | 54 22 00.6 | -8.84 ± 0.02 | 0.51 ± 0.02 | 0.45 ± 0.02 |
| 14 | 14 03 53.03 | 54 21 56.1 | -8.10 ± 0.02 | 0.23 ± 0.03 | 0.20 ± 0.03 |
| 15 | 14 03 53.35 | 54 22 00.5 | -8.87 ± 0.01 | 0.20 ± 0.01 | 0.17 ± 0.01 |
| 16 | 14 03 53.41 | 54 21 59.1 | -8.61 ± 0.01 | 0.41 ± 0.02 | 0.39 ± 0.02 |
| 17 | 14 03 53.58 | 54 22 04.0 | -8.03 ± 0.02 | 0.44 ± 0.03 | 0.42 ± 0.02 |
| 18 | 14 03 53.78 | 54 22 11.1 | -9.03 ± 0.02 | 0.28 ± 0.08 | 0.03 ± 0.03 |
| 19 | 14 03 53.98 | 54 21 56.1 | -8.24 ± 0.01 | 0.50 ± 0.02 | 0.48 ± 0.02 |
| 20 | 14 03 54.00 | 54 22 07.9 | -8.35 ± 0.02 | 0.19 ± 0.03 | 0.18 ± 0.03 |
| 21 | 14 03 54.10 | 54 22 02.5 | -8.30 ± 0.01 | 0.54 ± 0.02 | 0.41 ± 0.02 |
| 22 | 14 03 54.18 | 54 22 06.6 | -8.24 ± 0.02 | 0.33 ± 0.03 | 0.31 ± 0.03 |
| 23 | 14 03 54.19 | 54 22 11.2 | -9.17 ± 0.01 | 0.55 ± 0.01 | 0.51 ± 0.01 |
| 24 | 14 03 54.32 | 54 22 09.1 | -8.09 ± 0.05 | 0.10 ± 0.06 | 0.07 ± 0.06 |
| 25 | 14 03 54.74 | 54 21 53.7 | -8.20 ± 0.01 | 0.27 ± 0.01 | 0.24 ± 0.01 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
TABLE 5
PHOTOMETRY OF CANDIDATE CLUSTERS IN NGC 5471

| ID   | $\alpha$ (J2000.0) | $\delta$ (J2000.0) | $M_{F547M}$ | $M_{F547M} - M_{F675W}$ | $M_{F547M} - M_{F675W'}$ |
|------|-------------------|-------------------|-------------|--------------------------|--------------------------|
| 1*   | 14 04 28.64       | 54 23 51.9        | -8.81 ± 0.09| 1.24 ± 0.12              | 0.41 ± 0.11              |
| 2*   | 14 04 28.64       | 54 23 52.1        | -8.23 ± 0.12| -0.18 ± 0.06             | -0.13 ± 0.04             |
| 3    | 14 04 28.86       | 54 23 48.2        | -9.08 ± 0.03| -9.12 ± 0.06             | -9.05 ± 0.09             |
| 4    | 14 04 28.88       | 54 23 47.8        | -9.86 ± 0.02| -0.15 ± 0.03             | -0.12 ± 0.03             |
| 5    | 14 04 28.90       | 54 23 48.4        | -10.27 ± 0.01| -0.02 ± 0.02             | -0.07 ± 0.02             |
| 6    | 14 04 29.10       | 54 23 41.7        | -8.59 ± 0.04| -0.34 ± 0.09             | -0.09 ± 0.05             |
| 7    | 14 04 29.15       | 54 23 45.9        | -9.00 ± 0.06| -0.04 ± 0.09             | -0.11 ± 0.07             |
| 8    | 14 04 29.17       | 54 23 45.4        | -8.87 ± 0.06| 1.12 ± 0.08              | 0.14 ± 0.07              |
| 9    | 14 04 29.27       | 54 23 51.2        | -9.38 ± 0.01| 0.26 ± 0.03              | 0.19 ± 0.01              |
| 10   | 14 04 29.29       | 54 23 52.4        | -8.71 ± 0.08| 0.99 ± 0.11              | 0.14 ± 0.13              |
| 11   | 14 04 29.29       | 54 23 52.9        | -8.21 ± 0.05| 0.86 ± 0.09              | 0.22 ± 0.08              |
| 12   | 14 04 29.33       | 54 23 47.2        | -9.06 ± 0.02| 0.37 ± 0.04              | 0.19 ± 0.03              |
| 13   | 14 04 29.37       | 54 23 46.5        | -8.47 ± 0.04| 0.34 ± 0.04              | -0.04 ± 0.04             |
| 14   | 14 04 29.38       | 54 23 46.2        | -8.08 ± 0.06| 0.72 ± 0.08              | 0.35 ± 0.09              |
| 15   | 14 04 29.39       | 54 23 51.8        | -8.02 ± 0.02| 0.54 ± 0.14              | 0.02 ± 0.09              |
| 16   | 14 04 29.47       | 54 23 46.4        | -10.06 ± 0.06| 0.16 ± 0.13             | -0.13 ± 0.06             |
| 17   | 14 04 29.53       | 54 23 46.1        | -8.68 ± 0.14| 1.47 ± 0.15              | 0.25 ± 0.15              |
| 18   | 14 04 29.54       | 54 23 45.8        | -8.40 ± 0.11| 1.38 ± 0.13              | 0.52 ± 0.12              |
| 19   | 14 04 29.56       | 54 23 47.5        | -8.97 ± 0.02| 0.44 ± 0.07              | 0.21 ± 0.03              |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

* The photometry is given in two rows, with the first row measured with the WFC images and the second row measured with the PC images.

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**Fig. 8.** $M_{F547M}$ vs. ($M_{F547M} - M_{F675W}$) diagram of cluster candidates in NGC 5461. Observations of the clusters are plotted in filled circles. Additional circles are drawn around clusters that are in bright H ii regions. Evolutionary tracks generated from Leitherer et al. (1999) and BC03 for a Salpeter initial mass function and a metallicity of $Z = 1 Z_\odot$ are plotted in solid and dotted curves, respectively. Ages in megayears are marked along the evolutionary tracks. To avoid crowding, the Starburst99 evolutionary track is shown for a cluster mass of $5 \times 10^5 M_\odot$ and the BC03 track for $1 \times 10^4 M_\odot$. The reddening vectors of associated H ii regions are plotted in dashed arrows, and the possible dereddening vectors are marked with solid arrows for clusters brighter than $M_{F547M} = -9.0$. The R136 cluster is plotted as a reference point: reddened R136 in a filled triangle and dereddened R136 in an open triangle.

**Fig. 9.** $M_{F547M}$ vs. ($M_{F547M} - M_{F675W}$) diagram of cluster candidates in NGC 5462. Symbols are the same as in Fig. 8, with the addition of a dashed circle for the cluster candidate in a supershell. The evolutionary tracks are the same as in Fig. 8.
from their Balmer decrements by Kennicutt & Garnett (1996) and plot the corresponding reddening vectors in Figures 8–10. We have adopted these nebular extinctions and made reddening-corrected estimates of masses for clusters more luminous than $M_{\text{F547M}} = -9$. The age and mass estimates of these luminous clusters are given in Table 6. We do not attempt to estimate masses for fainter clusters because these luminosities overlap those of single supergiants (Humphreys & Davidson 1979). Furthermore, many faint clusters are not surrounded by bright nebulosity, indicating poorly constrained ages at greater than 10 Myr, so their mass estimates would be highly uncertain.

We have used the R136 cluster to estimate the uncertainties in our cluster mass estimates. From the extinction-corrected location of R136 in the CMD, we estimate a mass of $\sim 2 \times 10^4 M_\odot$. The mass of R136 has been derived from its resolved stellar content to be $2.2 \times 10^4 M_\odot$ (Hunter et al. 1995) by summing the masses of stars $\geq 2.8 M_\odot$ (mass cutoff limited by completeness) within a 4.7 pc radius. Note however that our estimate of mass is based on the luminosity of R136 within a 7 pc radius and a minimum stellar mass of $1 M_\odot$. Our mass estimate of R136 using the 4.7 pc radius aperture (Moffat et al. 1985) and the 2.8 $M_\odot$ lower mass limit is $1.4 \times 10^4 M_\odot$, about 40% lower than that derived from the resolved stellar content. Therefore, the uncertainties in our cluster mass estimates are at least 40%.

### 3.3. Assessing Cluster Sizes

Some of our clusters appear resolved in the PC images, so it is possible to determine their sizes. The size of a cluster can be described by its effective radius, $R_{\text{eff}}$, the radius that encircles half of the cluster light. The $R_{\text{eff}}$ of a cluster can be estimated with the routine ishape developed by Larsen (1999). In this routine, the surface brightness profile of a cluster is modeled by an analytic function and convolved with a point-spread function (PSF) calculated with the TINY TIM Version 6.0 (Krist 1995) for the cluster’s position on the PC chip. The PSF-convolved model profile is then compared with the observed cluster profile. The best-fit model, judged by the $\chi^2$ statistics, gives the full width at half-maximum (FWHM) of the analytic function, which is then used to determine $R_{\text{eff}}$.

We have used the two most common analytic functions, the Gaussian and the King (1962) profiles, to model the clusters. The King profile contains a concentration parameter $c = \log (r_c/r_t)$, where $r_t$ is the tidal radius and $r_c$ is the core radius. Typically $c$ is within the range of 1.0–2.0 for globular clusters in the Galaxy (Harris 1996) and young rich clusters in the LMC (Elson et al. 1987). We have experimented with different values of $c$ within this range in the model fits and found that for a cluster detected with S/N $\geq 15$, the best-fit $R_{\text{eff}}$ is insensitive to the concentration parameter $c$ or even the form of the analytic function. For a bright cluster with adequate S/N, the $R_{\text{eff}}$ is estimated using both the Gaussian and the King profiles, and the average of the two estimates is adopted and given in Table 6.

### Table 6

| Cluster ID      | Age (Myr) | Starburst99 Mass ($\times 10^4 M_\odot$) | BC03 Mass ($\times 10^4 M_\odot$) | $R_{\text{eff}}$ (pc) | Remarks                              |
|-----------------|-----------|------------------------------------------|----------------------------------|-----------------------|--------------------------------------|
| NGC 5461-1      | <5        | $2 \pm 0.5$                              | $2 \pm 0.5$                      | ...                   |                                      |
| NGC 5461-6      | <5        | $1 \pm 0.5$                              | $\leq 1$                         | $0.8 \pm 0.2$         |                                      |
| NGC 5461-8      | <5        | $1.5 \pm 0.5$                            | $1.5 \pm 0.5$                    | $0.7 \pm 0.2$         |                                      |
| NGC 5461-9      | <5        | $1.5 \pm 0.5$                            | $1 \pm 0.5$                      | ...                   |                                      |
| NGC 5461-10     | <5        | $3 \pm 1$                                | $2 \pm 1$                        | $2.1 \pm 0.1$         | Asymmetric morphology                |
| NGC 5461-11     | <5        | $\leq 0.5$                               | $\leq 0.5$                       | ...                   |                                      |
| NGC 5462-6      | >10       | $\leq 2$                                 | $1.5 \pm 2$                      | $2.3 \pm 0.3$         | Asymmetric morphology                |
| NGC 5462-18     | <5        | $\leq 1$                                 | $0.5 \pm 1$                      | ...                   |                                      |
| NGC 5462-23     | >10       | $\sim 2$                                 | $1.5 \pm 2$                      | ...                   |                                      |
| NGC 5471-2      | <5        | $\sim 0.2$                               | $\sim 0.2$                       | ...                   |                                      |
| NGC 5471-3      | >10       | $\sim 0.5$                               | $\sim 0.5$                       | ...                   |                                      |
| NGC 5471-4      | >10       | $\geq 1$                                 | $\geq 1$                         | $2.9 \pm 0.3$         | Asymmetric morphology                |
| NGC 5471-5      | >10       | $\sim 2$                                 | $\sim 2$                         | $1.4 \pm 0.1$         | Asymmetric morphology                |
| NGC 5471-7      | <5        | $\sim 0.5$                               | $\sim 0.5$                       | ...                   |                                      |
| NGC 5471-9      | >10       | $\sim 1$                                 | $\sim 1$                         | $0.2 \pm 0.1$         | Probably a star                      |
| NGC 5471-12     | <5        | $\sim 0.5$                               | $\sim 0.5$                       | ...                   |                                      |
| NGC 5471-16     | <5        | $1.5 \pm 0.5$                            | $1.5 \pm 0.5$                    | $1.1 \pm 0.1$         |                                      |

Fig. 10.—$M_{\text{F547M}}$ vs. ($M_{\text{F547M}} - M_{\text{F675W}}$) diagram of cluster candidates in NGC 5471. Symbols are the same as in Fig. 8. The evolutionary tracks are those generated for NGC 5461 and NGC 5462, but with a metallicity of $Z = 0.2$ $Z_\odot$.
All but one of the cluster sizes we measured are in the range of $R_{\text{eff}} = 0^\prime.02-0^\prime.09$, corresponding to 0.7–2.9 pc. (Note that $R_{\text{eff}}$ can be smaller than the pixel size of 0\textquotesingle 0455, because the PSF effects have been considered and removed in the profile fitting.) The only exception is NGC 5471-9, whose $R_{\text{eff}}$ is only 0\textquotesingle 005; as we discuss later in § 4.3, NGC 5471-9 is most likely a luminous A–F supergiant, instead of a cluster. The sizes of these M101 clusters are within the range of clusters in the Galaxy and nearby galaxies. For example, the globular clusters in the Galaxy have $R_{\text{eff}} \sim 1–5$ pc, with a median of $\sim 3$ pc (Harris 1996); the compact young cluster R136 in the LMC has $R_{\text{eff}} \sim 0.9$ pc (Mackey & Gilmore 2003);\(^3\) compact young massive clusters in nearby starburst galaxies where stars are not resolved have $R_{\text{eff}} \sim 2–4$ pc (Meurer et al. 1995). Comparisons between the M101 clusters and R136 will be discussed in more detail in § 4.

4. CLUSTERS IN THREE LUMINOUS GHRs IN M101

Below we describe the spatial distribution, ages, masses, and sizes of the clusters in NGC 5461, NGC 5462, and NGC 5471. The extinctions of individual H ii regions in these GHRs are taken from Kennicutt & Garnett (1996).

4.1. Clusters in NGC 5461

The GHR NGC 5461 has been loosely defined to be the H ii complex extending over a 66\textquotesingle\times 26\textquotesingle region in ground-based Hα images (Israel et al. 1975). Considering that this area corresponds to a linear size of $\sim 2.3$ kpc $\times$ 0.9 kpc, it is unlikely that the entire region is associated with one coherent star formation event. Indeed, 12 H ii regions have been identified within NGC 5461 by Hodge et al. (1990). Our WFPC2 Hα image shows that NGC 5461 contains two regions that would have been individually identified as GHRs if they were in the Local Group: H1105 and H1098 marked in Figure 5e (designation from Hodge et al. 1990). H1105 is 3 times as luminous as 30 Dor, and H1098 is as luminous as NGC 604, or one-third as luminous as 30 Dor. The 10 fainter H ii regions are distributed roughly along the axis connecting H1105 and H1098 with a higher concentration toward H1105. We define the “main body” of NGC 5461 to be the region containing H1105 and H1098 and their vicinity, as in the field of view of Figure 5.

The relationship between the stars/clusters and the H ii regions is clearly illustrated in the color image of NGC 5461 (Fig. 2). In addition to the bright H ii regions, NGC 5461 also has nebular filaments, loops, and well-defined shells with stars/clusters underneath these interstellar structures. A total of 12 cluster candidates are identified in the main body of NGC 5461; they are listed in Table 3 and marked in Figure 5f. Only six clusters have $M_{F547M} \leq -9$: five in H1105 (clusters 6, 8, 9, 10, and 11) and one in H1098 (cluster 1). A careful inspection of their immediate surroundings shows that all six clusters are superposed on bright H ii regions, indicating ages of less than 5 Myr. To estimate the masses of these young luminous clusters, we adopt the visual extinctions of $A_V = 1.7 \pm 0.4$ and $0.8 \pm 0.1$ of H1098 and H1105, apply the respective extinction correction, and compare the dereddened cluster positions in the CMD in Figure 8 with the evolutionary tracks generated by Starbursts99 and BC03 for different SSP masses. Four of the clusters (1, 6, 9, and 10) show dereddened colors consistent with SSPs at ages less than 5 Myr; thus their masses can be estimated in a straightforward manner. The two remaining clusters, on the other hand, have dereddened colors consistent with SSPs at ages greater than 6 Myr. The red colors of clusters 8 and 11 can be caused by large local extinction excesses or stochastic color deviation for low-mass SSPs. We consider the latter more likely, i.e., the cluster contains or is projected near a red supergiant and the cluster color is thus confused. For example, cluster 11 may consist of (or be projected toward) a K0 Ia–O supergiant with $M_V = -9.4$ (Humphreys 1978) and $(V' - R)_0 = 0.76$ (Johnson 1966) and a young cluster with $M_{F547M} = -9.2$. The masses of clusters 8 and 11 are determined with the ad hoc assumption of a contaminating red supergiant, which reduces the luminosity of the cluster and lowers the mass estimate accordingly. The mass estimates of the six brightest clusters in NGC 5461 are mostly in the range of $(1–3) \times 10^4 M_\odot$ (see Table 6). These masses are comparable to that of R136, $\sim 2 \times 10^4 M_\odot$.

The PC images of NGC 5461 are used to determine the cluster sizes, but only three clusters, 6, 8, and 10, are detected with $S/N \geq 15$ for reliable size measurements. The $R_{\text{eff}}$ estimated for these three clusters are 0.8, 0.7, and 2.1 pc, respectively. While the sizes of clusters 6 and 8 are comparable to that of R136, $R_{\text{eff}} = 0.9$ pc, cluster 10 is more extended and shows visible departure from spherical symmetry in the PC image in Figure 11. The morphology of cluster 10 suggests that it may be a composite of two clusters with the southwest object brighter than the northeast object.

Among the three GHRs we studied in M101, NGC 5461 is particularly interesting because it is one of the most luminous GHRs in galaxies within 10 Mpc (Kennicutt 1984). Furthermore, the core of NGC 5461 (i.e., H1105) has a remarkably high surface brightness with a peak emission measure of $4.4 \times 10^5$ cm$^{-6}$ pc, comparable to those of the most active starburst regions. The Hα luminosity of H1105 implies an ionizing flux rivaling those of SSCs (Kennicutt & Chu 1988; Luridiana & Peimbert 2001); thus, NGC 5461 has been considered the most promising site in M101 where SSCs might be found. However, our analysis shows that H1105 contains five R136-class clusters, which are by no means in the same league as the SSCs with masses $\sim 10^5–10^6 M_\odot$ commonly found in starburst galaxies or mergers (e.g., O’Connell et al. 1994; Whitmore et al. 1999). The core of NGC 5461 is nevertheless striking in its high concentration of stars in a small volume—three clusters with a total mass of $6 \times 10^{4} M_\odot$ in a region of $\sim 32$ pc (0\textquotesingle 09) across. It is possible that these clusters are subclusters that will dynamically interact and merge into a cluster that has a mass more typical for SSCs. As shown in the numerical simulations of Bonnell et al. (2003), the hierarchical fragmentation of giant molecular clouds naturally leads to the formation of subclusters that can merge to form the final stellar cluster. If H1105 were projected to a distance similar to that of the Antennae galaxies ($\sim 20$ Mpc, Whitmore et al. 1999), it would imitate a single cluster as shown in Figure 11b, and the combined light of the clusters and the bright stellar background in a 0\textquotesingle 2 radius aperture would have $M_{F547M} = -13.0$, corresponding to a mass of $\sim 10^5 M_\odot$. These results suggest that some young SSCs previously identified at distances of $\gtrsim 20$ Mpc may be tight groups of R136-class clusters as seen in the core of NGC 5461.

4.2. Clusters in NGC 5462

The GHR NGC 5462 corresponds to a large H ii complex with a dimension of 90\textquotesingle\times 34\textquotesingle, or 3.2 kpc $\times$ 1.2 kpc, in

\(^3\) The surface brightness profile of R136 indicates a compact, dominant component on top of a broad, shallow component. The $R_{\text{eff}}$ is estimated using its core radius of 0.32 pc and a King profile with $c = 1.5$ to approximate the compact component.
ground-based Hα images (Israel et al. 1975). Thirty-three H II regions have been identified within NGC 5462 (Hodge et al. 1990), but none are comparable to 30 Dor. The overall morphology of NGC 5462 consists of a few bright H II regions distributed along an axis from northeast to southwest and fainter filaments and loops extending outward from this axis. The two brightest H II regions, H1170 and H1176, are each only comparable to NGC 604, or one-third as luminous as 30 Dor; the others are much fainter. The distribution of star formation in NGC 5462 is apparently not as concentrated as in NGC 5461. We define the “main body” of NGC 5462 to be the region containing H1176, H1170, H1159, and their vicinity, as in the field of view of Figure 6.

The color image of NGC 5462 (Fig. 3) shows a distinct offset between the ionized gas and concentrations of stars, suggesting that the star formation has proceeded from the southeast to northwest. A total of 25 loosely distributed cluster candidates are identified in NGC 5462 (see Table 4 and Fig. 6f). Most of these clusters are faint; only three clusters, 6, 18, and 23, have $M_{F547M} < -9$ and are analyzed for their masses. While cluster 18 is superposed on a bright H II region H1176, indicating an age of less than 5 Myr, clusters 6 and 23 are not associated with any H II regions or supershells, indicating ages greater than 10 Myr. For cluster 18 the visual extinction $A_V = 0.9 \pm 0.4$ of the surrounding H II region H1176 is adopted, and for the other two clusters the visual extinctions of their nearest H II regions are adopted, i.e., $A_V = 0.6 \pm 0.2$ of H1159 for cluster 6 and $A_V = 0.9 \pm 0.4$ of H1176 for cluster 23. We apply the respective extinction correction to each of the three bright clusters and compare their dereddened cluster positions in the CMD in Figure 9 with the evolutionary tracks. The young cluster 18 shows a dereddened color consistent with SSPs at ages of $<5$ Myr and the estimated mass is $\leq 1 \times 10^4 M_\odot$. The two older clusters 6 and 23 show dereddened colors consistent with SSPs at ages of $>10$ Myr; however, as their ages are poorly constrained, we only obtain their lower mass limits by assuming cluster ages of $\sim 10$ Myr. We note that unless the two clusters have ages greater than 30 Myr, their masses would be within a factor of 1.5 of the lower mass limits. The mass estimates of the three brightest clusters in NGC 5462 are in the range of $(1-2) \times 10^4 M_\odot$ (see Table 6), comparable to the mass of R136.

In the PC images of NGC 5462, only cluster 6 is detected with S/N $\geq 15$ for size measurements. The $R_{eff}$ estimated for this cluster is 2.3 pc, more extended than that of R136. As shown in Figure 12, cluster 6 has an asymmetric morphology elongated along the northwest and southeast direction, indicating a complex structure.

NGC 5462 has the lowest Hα surface brightness among the three GHRs we studied in M101. It has a larger number of clusters than the other two GHRs, but only three are R136-class clusters. Furthermore, the clusters do not show obvious spatial concentrations, in sharp contrast to those seen in NGC 5461. The combination of the low Hα surface brightness and sparse distribution of small-mass clusters suggests that the star formation and cluster formation is more spread out and modest in NGC 5462.

4.3. Clusters in NGC 5471

The GHR NGC 5471 extends over a diameter of $\sim 17''$, or $\sim 600$ pc. Ground-based images of NGC 5471 show five bright knots, which are designated as the A, B, C, D, and E components by Skillman (1985) and have been called NGC 5471 A–E, respectively. Our color image of NGC 5471 (Fig. 4) shows that the A, B, C, and E components display bright H II regions centered on clusters. However, the D component displays an offset between the H II region and the clusters, which are located to the north and the east sides of a dark cloud, respectively; it is uncertain whether the clusters and the H II regions are physically associated. The A component is as luminous as 30 Dor, and the B, C, and E components are comparable to or fainter than NGC 604.

A total of 19 cluster candidates are identified in NGC 5471; they are listed in Table 5 and marked in Figure 7f. Most of
the clusters reside within the A–E components, with the highest concentration located in the A component and its western extension. The eight clusters with $M_{F547M} \leq -9$ have been analyzed. We have adopted the visual extinction of each component, applied the respective extinctions to the eight brightest clusters, and compared the dereddened cluster positions in the CMD with the evolutionary tracks (see Fig. 10). The comparisons are problematic because most of the dereddened cluster colors do not agree with those expected from the evolutionary tracks. While the disagreements are partially attributed to errors in the extinction and photometric measurements, the dominant cause of the disagreements is probably uncertainties in the stellar evolution models at low metallicities. It is known that at $Z/Z_\odot \leq 0.2$ stellar evolution models cannot reproduce the observed luminosities and colors of red supergiants or the number ratios of blue to red supergiants (Mayya 1997; Origlia et al. 1999; Leitherer et al. 1999). These uncertainties directly affect the luminosities and colors of SSPs, particularly at ages around 7–14 Myr when red supergiants are significant contributors of the total light. Given these uncertainties, we can make only order-of-magnitude mass estimates for the clusters in NGC 5471.

Four of the clusters we analyzed (2, 7, 12, and 16) are superposed on bright H II regions, suggesting that they are less than 5 Myr old. Clusters 7, 12, and 16 are only $\sim 0.1$ mag bluer or redder than those expected for young clusters; therefore, we disregard these color differences and use only the $M_{F547M}$ to estimate their cluster masses. Cluster 2, on the other hand, is $\sim 0.6$ mag redder than the color expected for its young age, and this discrepancy is larger than the known errors in photometry or stellar evolution models. We suggest that this red color excess is likely attributed to a contaminating postoutburst luminous blue variable (LBV) because cluster 2 is located in the C component where high-velocity (>1000 km s$^{-1}$), [N II]–bright nebular emission similar to that of $\eta$ Car’s ejecta nebula has been reported (Castaneda et al. 1990). We assume that cluster 2 contains an LBV similar to $\eta$ Car, which has $V = 6.22$ and $R = 4.90$ at quiescent states (Mendoza 1967) and can brighten up by 1–2 mag during outbursts or 3–5 mag during superoutbursts (Humphreys & Davidson 1994). These quiescent $V$ and $R$ magnitudes can be converted to $M_{F547M} = -8.5$ and $M_{F675W} = -9.4$ using the distance modulus of $(m-M)_0 = 12.79$ and the extinction of $A_V = 1.92$ for $\eta$ Car’s host cluster Trumpler 16 (DeGioia-Eastwood et al. 2001). The remaining members of cluster 2 would have $(M_{F547M} - M_{F675W}) = 0.44$, which is still too red for a less than 5 Myr old cluster. However, if the hypothesized LBV is 0.4 mag brighter (during or after an outburst), the rest of cluster 2 would have $(M_{F547M} - M_{F675W}) = -0.1$ as expected for a young cluster and $M_{F547M} = 8.2$. These resultant color and magnitude are used to estimate the mass of cluster 2.

The other four clusters we analyzed (3, 4, 5, and 9) are not associated with H II regions or supershells, suggesting that their ages are greater than 10 Myr. However, as discussed in the next paragraph, 9 has a small intrinsic size that makes it more likely a luminous supergiant rather than a cluster. Among the
remaining clusters, 4 shows a dereddened color consistent with SSPs at ages greater than 10 Myr, and thus its lower mass limit is easily estimated. Clusters 3 and 5, on the other hand, have dereddened colors ~0.2 mag bluer than that of SSPs at ages greater than 10 Myr. Since their extinction corrections are already small, the disagreements are unlikely to be caused by the uncertainty in extinction measurements. It is most likely that the disagreements arise from the uncertainties in the modeled colors and photometry, so we disregard the blue color excesses when estimating the cluster masses. The mass estimates for the eight bright clusters are in the range of \( M = (0.5-2) \times 10^4 \, M_\odot \) (see Table 6), approaching or comparable to R136.

NGC 5471 has a large number of young clusters with ages less than 5 Myr. However, the majority of these young clusters are faint with \( M_{F547M} \geq -9 \), which may be small clusters with masses of a few times \( 10^4 \, M_\odot \) or just luminous supergiants. Among the cluster candidates in NGC 5471, 4 and 5 are the most massive ones since they are older than 10 Myr and still as luminous as the young R136 cluster, suggesting that their masses are higher that of R136.

5. DISCUSSION

5.1. Nature of Faint Cluster Candidates in GHRs

A large number of cluster candidates have been identified in the three M101 GHRs, but the nature of the faintest objects is uncertain. It is possible that some of these faint cluster candidates consist of multiple OB associations as observed in the nearby GHR NGC 604 (Hunter et al. 1996) and some are simply luminous supergiants frequently seen near high concentrations of massive stars, such as 30 Dor (Walborn & Blades 1997). We have therefore simulated WFPC2 images of 30 Dor and NGC 604 at a distance of 7.2 Mpc and searched for “clusters” using the same criteria as we did for cluster candidates in the M101 GHRs. The spurious clusters in 30 Dor and NGC 604 can be identified because their resolved stellar contents are known. The real and spurious clusters in these two GHRs can then be compared with the cluster candidates in M101 to better assess the nature of the latter.

To simulate a WFPC2 image of 30 Dor at 7.2 Mpc, we have used a green continuum (\( \lambda_c = 5130 \, \AA, \Delta \lambda = 155 \, \AA \)) image from the Magellanic Clouds Emission-Line Survey (MCELS; Smith et al. 1999) and binned the data to 3.5 pc per pixel. The resultant image is displayed in Figure 13a. Using the same identification criteria for clusters in M101 GHRs, the two brightest objects in 30 Dor will be selected as clusters: R136 and R131. While R136 is a bona fide cluster, R131 (=HD 269902) is an A0 supergiant with \( V = 10.0 \) (corresponding to \( M_V + A_V = -8.5 \))
and hence a spurious cluster. The misidentification of R131 as a cluster bolsters our choice of a luminosity cutoff of $M_{F547M} = -9.0$ for cluster mass estimates ($\gtrsim 3.2$), as the fainter cluster candidates may be single supergiants. It is interesting to note that two other concentrations of stars in 30 Dor are not identified as clusters: the Hodge 301 cluster (Hodge 1988) and the OB association LH 99 (Lucke & Hodge 1970). The Hodge 301 cluster, with an age of $\sim 20–25$ Myr and a mass of a few $10^5 M_\odot$ (Grebel & Chu 2000), is too faint to meet our cluster identification criteria. LH 99, on the other hand, is too distributed to mimic a cluster.

A WFPC2 image of NGC 604 at 7.2 Mpc is simulated with its archival WFPC2 F547M image. Adopting a distance of 0.84 Mpc to M33 (Freedman et al. 1991), the data are binned to 3.5 pc per pixel, and the resultant image is displayed in Figure 13b. The OB associations in NGC 604 appear as small concentrations on top of an irregular stellar background. The four brightest concentrations have $M_{F547M} = -8.0$ to $-9.0$, luminous enough to meet our identification criteria for M101 clusters. However, most of the concentrations have irregular shapes, and the brightest one does not even have an obvious boundary. Therefore, the NGC 604–type OB associations may mimic faint clusters at best, with luminosities rivaled by those of supergiant stars.

For a direct comparison between M101 GHRs and the simulated 30 Dor and NGC 604 at 7.2 Mpc, Figure 13 displays their images in the same spatial and intensity scales over a 350 pc $\times$ 350 pc field of view. It is immediately clear that the brightest cluster candidates in M101 GHRs are more luminous than R136 and are most likely bona fide clusters. The nature of the cluster candidates fainter than $M_{F547M} = -9.0$, marked in Figure 13, is less obvious. Some faint cluster candidates may be blue supergiants because they have sharp images and appear isolated, and the blue color excludes the possibility of post–core-collapse clusters; examples of these include NGC 5461-7, NGC 5462-20, and perhaps NGC 5471-13 and 14. Some faint cluster candidates may be OB associations because they appear extended without a sharp boundary; examples of these include NGC 5461-5, NGC 5462-13 and 15, and NGC 5471-10, 11, and 17.

5.2. The Fraction of Massive Stars Formed in Clusters

It has been suggested that massive stars form preferentially in associations and clusters (Stahler et al. 2000 and references therein). Our HST WFPC2 images of the M101 GHRs show that several young R136-class clusters are superposed on discrete regions of unresolved stellar emission, e.g., clusters 8, 9, and 10 at the core of NGC 5461 and cluster 16 at the core of NGC 5471A. The unresolved stellar backgrounds are most likely star clouds that contain field stars and loosely assembled associations. The similarities in locations and colors suggest that the clusters and the background star clouds are formed from the same episode of star formation. It is then interesting to determine the fraction of massive stars that are formed in R136-class clusters in these regions. We have used two different methods to determine this fraction: one is based on the contribution of cluster light to the total light, and the other is based on a comparison between the ionization flux expected from the clusters and the ionizing flux required by the surrounding H$\alpha$ region.

We have selected four regions for this analysis: two in NGC 5461, one in NGC 5462, and one in NGC 5471. These regions are listed in Table 7, and their close-up F547M and H$\alpha$ images are presented in Figure 14. The F547M images show that the clusters in these four regions are all superposed on discrete bright diffuse stellar backgrounds, and the H$\alpha$ images show that all are at the cores of bright compact H$\alpha$ regions. We have measured the total light from these four regions in both F547M and F675W bands using the apertures marked on the F547M images in Figure 14 and described in column (3) of Table 7. The background, determined from the median of an annular region outside the H$\alpha$ region, has been subtracted; although it contributes to only 1%–2% of the total light. For the clusters, we have applied aperture corrections of $\sim 0.2$ mag to our photometric measurements made with a 0$''$2 radius apphot aperture to account for the missing light. The cluster-to-total light ratios, $L_{\text{cluster}}/L_{\text{total}}$ given in columns (4) and (5) of Table 7, are in the range of 0.25–0.5; the uncertainties are dominated by the photometry and aperture corrections of the clusters, as they are superposed on bright local stellar background. The light ratios are slightly larger in the F547M band than in the F675W band, because the clusters are 0.1–0.2 mag bluer than their diffuse stellar background. This color difference can be caused by an age difference of a few megayears, assuming that the clusters and the underlying star clouds have the same initial mass function. As the precise ages are unknown, we cannot model the star clouds to determine their masses; therefore, the cluster-to-total light ratio can be considered only as an approximation of the fraction of massive stars formed in clusters. In the four regions we analyzed, about 25%–50% of the massive stars are formed in R136-class clusters.

The H$\alpha$ images in Figure 14 show that the H$\alpha$ regions around the clusters have rather well-defined boundaries where
the surface brightness drops off sharply. Such morphology suggests that the H ii regions are likely ionization-bounded or optically thick to ionizing radiation. We have measured the Hα fluxes\(^5\) of these four regions using the apertures marked on the Hα images in Figure 14 and described in column (6) of Table 7. The continuum-subtracted Hα images are used for the flux measurements, and extinction corrections are made. Assuming a 10\(^4\) K optically thick H ii region, the derived Hα luminosity, \(L_{\text{Hα}}\), can be used to determine the required ionizing luminosity, \(Q(H^\beta)\), through the relation

\[
Q(H^\beta) = 7.4 \times 10^{11} L_{\text{Hα}} \text{ photons s}^{-1},
\]

where \(L_{\text{Hα}}\) is in units of ergs s\(^{-1}\). The resultant ionizing luminosities (\(Q(H^\beta)\)) of the four regions are given in column (7) of Table 7.

The ionizing luminosity expected from the clusters at different ages can be calculated using the Starburst99 models. The ages of the clusters in the four selected regions are less than 5 Myr, as indicated by the associated bright H ii regions. Unfortunately, during the first 5 Myr a cluster’s ionizing luminosity decreases rapidly, dropping from the maximum at ~1 Myr to a factor of 5–7 lower at 5 Myr (Leitherer et al. 1999); therefore, the uncertainty in cluster age directly propagates into the uncertainty in ionizing luminosity of a cluster. We have adopted a cluster age of 3 Myr and calculated the expected ionizing luminosities of the clusters (\(Q_{\text{cluster}}\)) and their ratios to those required by the surrounding H ii regions. These results are given in columns (8) and (9) of Table 7. These ratios, 0.2–0.6, can be viewed as a very crude approximation of the fractions of massive stars formed in clusters. An interesting corollary of this result is that the ionizing luminosity, or Hα luminosity, of an H ii region is not a sufficient diagnostic for the existence of SSCs because the majority of stars may reside outside clusters.

In the four regions of star formation we considered, the fraction of massive stars in clusters estimated from the cluster-to-total light ratio is, within the uncertainties, consistent with that estimated from the cluster-to–H ii–region ionizing luminosity ratio—no more than about half of the massive stars are formed in the R136-class clusters. On the other hand, some R136-class clusters, such as 4 and 5 in NGC 5471D, are not superposed on a bright stellar background and constitute the dominant components in their associated episode of star formation. The fraction of stars formed in clusters must cover a range, which varies according to the physical conditions of star formation.

5.3. Interstellar Environments of the GHRs

We examine the distribution of interstellar molecular clouds and H i gas in the three M101 GHRs in order to gain insight on the cluster formation process. Molecular CO observations of these GHRs have been made by Giannakopoulou-Creighton et al. (1999) using both single-disc telescopes and interferometers. NGC 5461 has the strongest CO emission among the three GHRs, and its CO peaks appear concentrated toward the peaks of the Hα emission (see Fig. 4 in Giannakopoulou-Creighton et al. 1999), where the massive clusters are located. The CO emission toward NGC 5462 is detected in single-disc observations but not in interferometric observations, indicating that the molecular gas is distributed over a scale larger than the synthesized beam, ~3′′. No CO emission is detected in NGC 5471, which may be attributed to its low metallicity. In the two GHRs where CO is detected, the distribution of

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5 Owing to the ~300 km s\(^{-1}\) redshift of M101, two corrections need to be considered. First, the filter transmission of the redshifted Hα line is ~93% of the peak transmission, thus the extracted Hα flux should be multiplied by a correction factor of 1.07. Second, the [N ii] \(\lambda6548\) line is redshifted into the Hα bandpass at ~91% of the peak transmission and needs to be removed. The [N ii] contamination, estimated from the [N ii]/Hα ratios reported by Kennicutt & Garnett (1996), amounts to 1%–3% of the Hα flux in most cases.
molecular clouds is similar to that of clusters: concentrated in NGC 5461 and distributed in NGC 5462.

The distribution of H i gas in M101 and its relation with ionized gas have been reported by Smith et al. (2000, see their Figs. 1–2). Their H i map shows that NGC 5461 and NGC 5462 are in the same spiral arm. Assuming a trailing arm, the offsets of H i ridge downstream from the stars in NGC 5461 and NGC 5462 are consistent with the expectations of star formation triggered by density waves (Roberts 1969). NGC 5471 has a concentration of H i gas but the large-scale distribution of H i show a complex interarm structure, which may have resulted from tidal interactions during the last $10^9$ yr (Waller et al. 1997 and references therein). As H i gas can be produced by photodissociation of the natal molecular clouds (Allen et al. 1985; 1986; Smith et al. 2000), converted to H ii by photoionization and dispersed by fast stellar winds and supernova explosions, the distribution of H i does not provide adequately pertinent information about the cluster formation.

To study the physical conditions for cluster formation, it is necessary to examine the interstellar environment of the youngest clusters before the interstellar conditions have been altered by stellar energy feedback. The embedded young clusters that are observable in the infrared but not yet in the optical wavelengths (e.g., Kobulnicky & Johnson 1999; Turner et al. 2000; Johnson & Kobulnicky 2003) provide promising locations to study the physical conditions of cluster formation.

5.4. Cluster Luminosity Function

The luminosity functions (LFs) of young compact clusters have been studied in various types of galaxies with different star formation rates as a means to gain insight into the cluster formation process. To first order, the measured LFs for young compact cluster systems in merging or starburst galaxies are remarkably universal and can be approximated by a power law of the form $dN(L)/dL \propto L^{-\alpha}$, with the exponent $\alpha \approx -2 \pm 0.2$ (see Whitmore 2003 and references therein). The cluster LFs for a sample of nearby nonstarburst spiral galaxies also show similar $\alpha$, $-2.0$ to $-2.4$ (Larsen 2002). It has been suggested that this roughly universal LF is the result of fractal structure in turbulent gas (Elmegreen & Efremov 1997). Since the three M101 GHRs show different age and spatial distributions of clusters, it is interesting to intercompare their cluster LFs and see whether they also follow the universal cluster LFs.

The LFs of clusters in NGC 5461, NGC 5462, and NGC 5471 are presented in Figure 15. These LFs are constructed using raw $M_{F547M}$ (without extinction correction). No completeness correction to the LFs is needed because the cutoff of our sample at the faint end, $m_{F547M} \leq 21.3$, is much brighter than the detection limit, $m_{F547M} \sim 25.5$. Note however that the two faintest bins, $M_{F547M} = -8.0$ to $-9.0$, should be viewed with caution, as some of the “clusters” may be spurious, as discussed in § 5.1. The number of clusters in each GHR is modest, so we have also constructed a combined cluster LF of the three GHRs, shown in the bottom panel of Figure 15. We have carried out linear least-squares fits to the logarithmic LFs of clusters for the three GHRs individually and combined. The logarithmic LFs of clusters in the individual GHRs appear to have different slopes; the best-fit slopes for NGC 5461, NGC 5462, and NGC 5471 are $-1.5 \pm 0.3$, $-3.0 \pm 0.2$, and $-1.9 \pm 0.4$, respectively. The logarithmic LF of clusters in all three GHRs has a best-fit slope of $-2.3 \pm 0.1$.

Compared with the universal cluster LFs, NGC 5461 and NGC 5471 are on the flatter side, and NGC 5462 is on the steeper side. The small difference between NGC 5461 and NGC 5471 is not statistically significant, as each has only a small number of clusters and the numbers of clusters in the brightest bins are only 1–2. On the other hand, it may be statistically significant that NGC 5462 has a much steeper LF than NGC 5461 and NGC 5471, or NGC 5462 has a larger proportion of low-mass clusters. It is possible that the slope of a cluster LF varies according to the interstellar environment at the time when clusters were formed. As discussed in § 5.3, the current molecular environments of NGC 5461 and NGC 5462 are quite different, with molecular CO highly concentrated in NGC 5461 and diffuse in NGC 5462. The cluster LF for NGC 5461, NGC 5462, and NGC 5471 combined has an $\alpha$ within the range of the universal value, $-2$ to $-2.4$. If clusters in spiral or starburst galaxies are formed under conditions similar to NGC 5461 and NGC 5462 in random proportions, the cluster LFs should show a larger range of...
the cluster LF of a galaxy would be biased toward an LF similar to those of NGC 5461 and NGC 5471; therefore, the cluster LF of a galaxy would be biased toward \( \alpha = -2 \).

5.5. Evolutionary Aspects of the Clusters

The cluster mass, age, and size distribution of a cluster system may be used to investigate the dynamic evolution of clusters. Recent studies of rich clusters in the LMC have shown that the spread in core radius increases with cluster age, suggesting that all clusters were formed with small core radii but subsequently some experienced core expansion while others did not (Elson et al. 1989; Mackey & Gilmore 2003). It would be interesting to examine the clusters in M101 GHRs to see whether they follow the same core radius-age relation.

The mass, age, and core radius of the LMC clusters have been derived by Mackey & Gilmore (2003), using the Fioc & Rocca-Volmerange (1997) IMF slope, and a stellar mass range of 0.1–120 \( M_\odot \). To compare the M101 clusters with the LMC clusters, we have followed the Mackey & Gilmore (2003) method and reestimated the masses of M101 clusters, using the same code, IMF slope, and stellar mass range. The new cluster mass estimates are \( \sim 2–3 \) times as high as the cluster masses estimated earlier in this paper, owing to the addition of stars in the mass range of 0.1–1 \( M_\odot \). The M101 clusters are not sufficiently resolved for measurements of their core radii (\( r_c \)); therefore, we have adopted the relation \( r_c \sim 0.35 R_{\text{eff}} \) derived from a King profile with a concentration parameter of \( c = 1.5 \), a median value for LMC clusters (Elson et al. 1987). The core radii of M101 clusters thus estimated are 0.25–1 pc, and may be uncertain by up to a factor of 2, if its concentration parameter spans the same range as that in the LMC clusters.

To compare the M101 clusters with the LMC clusters, we present a three-dimensional diagram of cluster mass, age, and core radius in Figure 16. The data of the LMC clusters are adopted from Mackey & Gilmore (2003). The M101 clusters are plotted in open rhombuses, while the LMC clusters are plotted in filled ellipses, with the R136 cluster in a larger ellipse for easy identification. The M101 cluster masses were estimated using apertures of 7 pc radius, so we repeated Mackey & Gilmore’s derivation of the mass of R136 using this larger aperture and obtained a mass that is 40% higher, shown as a large open ellipse in Figure 16. While the LMC clusters span a large age range and show an increasing spread in core radii with the cluster age, the M101 clusters we analyzed are all young and small, sharing a similar parameter space with the R136 cluster. Among the small number of M101 clusters with size measurements, the younger clusters are generally smaller, but the accuracy of the size measurements is too limited by the linear resolution for definitive conclusions.

Finally, we discuss the disruption time of our M101 clusters and investigate whether dynamical evolution has caused a significant mass change in these clusters. The disruption time can be assessed empirically from the break in slopes of the logarithmic age distribution of clusters (Boutloukos & Lamers 2003) or from comparisons with N-body simulations (Baumgardt & Makino 2003). Recent studies using the empirical method have shown that the disruption time for a \( 10^5 \) \( M_\odot \) cluster varies greatly among galaxies, from \( 10^7 \) to \( 10^{10} \) yr, with the shortest being \( \sim 30–40 \) Myr in M82 and at 1–3 kpc from the nucleus of M51 (Boutloukos & Lamers 2003; de Grijs et al. 2003). Our M101 clusters in GHRs are apparently younger than these disruption timescales. Thus we determine the disruption time, \( T_{\text{dis}} \), following the simulations of Baumgardt & Makino (2003):

\[
\frac{T_{\text{dis}}}{\text{Myr}} = \beta \left[ \frac{N}{\ln (\gamma N)} \right]^{x} \frac{R_G}{kpc} \left( \frac{V_G}{220 \text{ km} \text{s}^{-1}} \right)^{-1},
\]

where \( R_G \) is the galactocentric radius, \( V_G \) is the circular velocity in a galaxy, \( N \) is the number of stars in a cluster, \( \beta \sim 1–2, \gamma = 0.02, \) and \( x \sim 0.8 \). For a cluster with a Salpeter mass function and a stellar mass range of 1–100 \( M_\odot \), the average mass of a star is 3.09 \( M_\odot \) and the number of stars is \( N = \text{cluster mass}/(3.09 \ M_\odot) \). NGC 5461 and NGC 5462 have \( R_G \sim 10 \) kpc and \( V_G = 185 \) km s\(^{-1}\), and NGC 5471 has \( R_G \sim 25 \) kpc and \( V_G = 195 \) km s\(^{-1}\) (Roberts & Rots 1973). A \( 10^4 \ M_\odot \) cluster in NGC 5461/NGC 5462 or NGC 5471 would have disruption times of \( (2.4–4.8) \times 10^{7} \) and \( (5.8–11.6) \times 10^{6} \) yr, respectively. The real disruption time must be shorter because the above estimates do not take into account processes that are important in disrupting clusters in GHRs, i.e., interactions with other clusters and with giant molecular clouds. In cases where massive clusters are concentrated in a small volume, such as the core of NGC 5461, cluster merger is a more important dynamic process and operates in a much shorter timescale than tidal disruption (Bonnell et al. 2003). Future simulations of dynamical evolution of clusters in GHRs using realistic conditions are needed.

6. SUMMARY

GHRs contains high concentrations of massive stars; thus, they provide an excellent laboratory to study modes of massive star formation and possible sites to form globular clusters. We have selected three very luminous but morphologically different GHRs in M101, NGC 5461, NGC 5462, and NGC 5471, to determine their cluster content in order to understand cluster formation in different environments. We have obtained HST WFPC2 images of these GHRs with the F547M and F675W continuum filters and the F656N H\( \alpha \) filter. The continuum
images are used to identify cluster candidates in each GHR and to carry out photometric measurements, and the H$\alpha$ images are used to examine the distribution of interstellar gas and to determine the ionizing flux requirement.

We have used the Leitherer et al. (1999; Starburst99) and BC03 population synthesis models to compute the colors and magnitudes of clusters of different ages and masses. The colors of a cluster are dependent on its age; however, our two continuum passbands are not blue enough to be sensitive to young massive stars for age determination. Therefore, we use the distribution of ionized interstellar gas to estimate the approximate cluster ages, then compare the measured colors and magnitudes of cluster candidates to the synthetic evolutionary tracks to determine their masses. To avoid confusion by luminous single supergiants, only cluster candidates more luminous than $M_{F547M} = -9.0$ are analyzed for their masses.

NGC 5461 is dominated by a very luminous core and has been suggested as a likely host of SSCs (Kennicutt & Chu 1988; Luridiana & Peimbert 2001). Our observations show that the core of NGC 5461 contains three R136-class clusters superposed on a bright stellar background in a small region $\sim 32$ pc across. It is possible that the three R136-class clusters will dynamically interact and merge into an SSC. If NGC 5461 were at a distance $\geq 20$ Mpc, the clusters at its core would appear as a single cluster and the total light would be $M_{F547M} = -13.0$, corresponding to a mass of $\sim 10^5 M_\odot$, reaching those of SSCs. It is possible that some of the previously reported SSCs at large distances are actually made up by tight groups of R136-class clusters similar to those in NGC 5461.

NGC 5462 consists of numerous loosely distributed H II regions that are individually much fainter than 30 Dor. Its clusters also show a loose distribution across the GHR. NGC 5462 has the largest number of clusters among the three GHRs studied, but most of the clusters are older than 10 Myr and fainter than $M_{F547M} = -9.0$.

NGC 5471 contains multiple bright H II regions, some of which are comparable to 30 Dor. A large number of cluster candidates are identified in NGC 5471; the majority of the clusters are fainter than $M_{F547M} = -9.0$, and they are in bright H II regions. The mass determination for clusters in NGC 5471 is problematic because the observed cluster colors are bluer than those spanned by the synthetic cluster evolutionary tracks for $Z = 0.2 Z_{\odot}$, possibly as a result of uncertainties in stellar evolution models at low metallicities. The cluster masses are thus estimated from the magnitudes alone and may be subject to large errors.

The most massive clusters in the three GHRs are in the mass range of $\sim (1-3) \times 10^4 M_\odot$, similar to R136. Two clusters in NGC 5471 might be more massive as they are not surrounded by H II regions and are each as luminous as R136; these two may be the most massive clusters in the three GHRs studied. No SSCs are present in any of the three GHRs. We have also estimated the sizes of some clusters on their PC images, using the routine developed by Larsen (1999). The effective radii of these clusters are in the range of 0.7–2.9 pc, ~1–3 times that of R136 (Mackey & Gilmore 2003).

To understand the makeup of the faint cluster candidates, we have simulated WFC2 images of 30 Dor and NGC 604 at the distance of M101. We find that single supergiants similar to R131 and OB associations as those in NGC 604 may contribute to the population of faint clusters ($M_{F547M} > -9.0$) in distant galaxies, while clusters similar to Hodge 301 or OB associations similar to LH 99 will be too faint or too extended to be identified as clusters even in M101.

The three M101 GHRs show different cluster LFs. The cluster LFs of spiral galaxies can be described by a power law with the exponent $\alpha$ in the range of $-2.0$ to $-2.4$ (Larsen 2002). We find that the cluster LFs of NGC 5461 and NGC 5471 are on the flatter side of the range, but the number of clusters is small in each GHR. NGC 5462 has the largest number of clusters and its cluster LF is significantly steeper, with $\alpha = -3.0 \pm 0.2$. It is possible that the clusters in NGC 5462 were formed in a low-pressure, low-concentration interstellar environment. The combined cluster LF of the three GHRs has an $\alpha$ of $-2.3 \pm 0.1$, well within the range for those of spiral galaxies. The universality of cluster LFs may be a statistical result from a cluster population with an observational bias toward the most luminous clusters.

The distribution of molecular clouds is concentrated in NGC 5461 and diffuse in NGC 5462, similar to the spatial distribution of their clusters. The diffuse interstellar environment and the larger proportion of low-mass clusters (steep cluster LF) of NGC 5462 qualitatively support the hypothesis that massive clusters are formed in high-pressure, high-concentration interstellar medium.

We have estimated the fraction of massive stars formed in clusters using (1) clusters’ contribution to the total stellar continuum and (2) comparison between the ionizing flux expected from the clusters and the ionizing flux required by the associated H II region. Both methods show that 50% of massive stars are formed in R136-class clusters. Consequently, the H$\alpha$ luminosity of an H II region does not provide a sufficient diagnostic for the existence of SSCs.

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