MULTIWAVELENGTH STUDY OF YOUNG MASSIVE STAR CLUSTERS
IN THE INTERACTING GALAXY ARP 24

CHEN CAO\textsuperscript{1,2} AND HONG WU\textsuperscript{1}

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ABSTRACT

We made a multiwavelength study of young massive star clusters (YSCs) in the interacting galaxy Arp 24 using optical and ultraviolet images from the Hubble Space Telescope (HST), the Sloan Digital Sky Survey, and the Galaxy Evolution Explorer; mid-infrared images from the Spitzer Space Telescope, and narrowband H$\alpha$ images and optical spectra from the National Astronomical Observatories of the Chinese Academy of Sciences 2.16 m telescope. Based on the HST images, we found that the brightest infrared knot in Arp 24 is associated with a complex of five YSCs within a region of $\sim$0.95\arcmin radius (127 pc) in size. The ages and masses of the star clusters in this complex and other regions were estimated using HST broadband photometries and the Starburst99 synthesis models. The star clusters in this complex are very young (within ages of $\sim$3–5 Myr) and massive (masses of $\sim$10$^5$ $M_\odot$). The ionization parameter and metallicity of the complex were estimated using the emission-line ratios, and the star formation rates were calculated using monochromatic 24 $\mu$m, far-ultraviolet, and H$\alpha$-line luminosities. We speculate that Arp 24 may have formed in a retrograde flyby encounter indicated by its one-armed appearance and fanlike structure, and the formation of the YSCs in this galaxy was triggered by the interaction. The clusters in the YSC complex may have formed in a single giant molecular cloud simultaneously. From the ultraviolet to mid-infrared spectral energy distributions, we found that the region of the YSC complex is relatively bluer in the optical and has higher 24 $\mu$m dust emission relative to the starlight and 8 $\mu$m emission. This warm infrared color may due to a strong UV radiation field or other mechanisms (e.g., shocks) within this region that may destroy the polycyclic aromatic hydrocarbons and enhance the small-grain emission at 24 $\mu$m.

Key words: galaxies: individual (Arp 24) — galaxies: interactions — galaxies: ISM — galaxies: star clusters — infrared: galaxies — stars: formation

Online material: color figures

1. INTRODUCTION

Star formation in galaxies generally occurs in star clusters instead of isolated stars; at least 20% of stars, and possibly all of them, form in clusters or associations (Fall 2004). Young massive star clusters (YSCs, with masses often $>10^5$ $M_\odot$), which are thought to be the products of violent star-forming episodes triggered by galaxy collisions, mergers, and close encounters (de Grijs 2003, 2004 and references therein), or generally form in the disks of isolated spirals with higher efficiency in environments with a high star formation rate (SFR) (Larsen 2004a and references therein), are important for the study of ongoing star formation, stellar populations, and the evolutionary histories of their parent galaxies. YSCs are thought to be formed in giant molecular clouds (GMCs) and concentrated in star-forming clumps (overdense regions, or cores; e.g., Elmegreen 2004).

The majority of important studies of extragalactic star clusters in the last few years have involved the use of the Hubble Space Telescope (HST), with its unprecedented spatial resolution ($\sim$0.04\arcsec) and full UV/optical band (0.1–1.0 $\mu$m) capability, for studying stellar populations, in particular, the blue coverage for age-dating young clusters (e.g., de Grijs et al. 2003; Larsen 2004b). The ages and masses of star clusters can be estimated using color-magnitude and/or color-color diagrams and compared with stellar population synthesis models (e.g., Johnson et al. 2003; Harris et al. 2004). Previous studies of extragalactic star clusters paid more attention to their general properties based on optical images, such as their luminosity and mass functions (e.g., Whitmore et al. 1999; Elmegreen et al. 2001), their sizes (e.g., Larsen 1999), and the mechanisms of cluster formation and disruption (e.g., Elmegreen 2004).

Nevertheless, mid-infrared observations of extragalactic star clusters are also very important for understanding the properties of heavily obscured clusters (e.g., Bontemps et al. 2001) and the dust environments of young cluster-forming systems (e.g., Zhang et al. 2001). The observations of the Spitzer Space Telescope (Werner et al. 2004) in the mid-infrared, with higher sensitivity and better angular resolution than previous observations (e.g., the Infrared Space Observatory [ISO]), provide a new opportunity to study both young and old stellar populations and star formation in normal (e.g., Pahre et al. 2004; Wu et al. 2005; Calzetti et al. 2005), starburst (Cannon et al. 2005, 2006a, 2006b), and interacting/merging (e.g., Wang et al. 2004; Smith et al. 2005; Elmegreen et al. 2006) galaxies. The four IRAC bands from 3.6 to 8.0 $\mu$m probe both stellar continuum and warm dust emission (of polycyclic aromatic hydrocarbons [PAHs] and dust-continuum), and the MIPS 24 $\mu$m band probes the warm dust emissions from very small grains (VSGs). Although Spitzer images are unable to resolve individual star clusters that can be well resolved by HST, they can be used to study the mid-infrared properties of the infrared-bright knots/clumps, which may be collections of OB associations and dense clusters of several hundred parsecs in size (Efremov 1995; Elmegreen et al. 2006).

Arp 24 (NGC 3445) forms a triplet with NGC 3440 and NGC 3458, at a separation of 9.9$^\prime$ and 14.0$^\prime$, respectively. Numerous H II region candidates exist in its spiral arm and disk. At the end of its southern spiral arm is a shred that may be a separate galaxy or may have been one in the past. Arp 24 is at a distance of...
27.6 Mpc (1" corresponds to 134 pc), with a total infrared luminosity of $L_{\text{IR}} \sim 4.8 \times 10^9 L_\odot$ (Bell 2003). Van den Bergh (1995) classified it as a "transitional object" that appeared intermediate between spirals that have central bulges and objects with central regions that are resolved into stars and knots. Böker et al. (2002, 2003) found that it contains a nuclear star cluster in the central region instead of a spiral bulge. Arp 24 is a target of the Spiral, Bridges, and Tails Guest Observer Cycle 1 Spitzer program (principal investigator [PI]: C. Struck), which is for studying the distribution of star formation in a sample of colliding galaxies with a wide range of tidal and splash structures (see Smith et al. [2005, 2007] and Hancock et al. [2006] for details).

In this paper we present an analysis of data from HST, Spitzer, Sloan Digital Sky Survey (SDSS), Galaxy Evolution Explorer (GALEX), Hα, and spectroscopic observations to study the properties and possible formation scenarios of the YSCs in the interacting galaxy Arp 24. The observations and relevant data reduction are presented in § 2; results on the multiwavelength emissions from the YSCs, the discovery of a YSC complex (YSCC), and other physical properties of the YSCs are described in § 3. Possible formation scenarios of the YSCs, and the PAH and warm dust emissions of the infrared knots in this system, are discussed in § 4. The major results of this work are summarized in § 5.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Optical and Ultraviolet Images

The U-band (F300W) and I-band (F814W) images of Arp 24 were taken with WFC2 on board HST, with exposure times of 600 and 640 s, respectively. The images were obtained as B associations from the ESO/ST-ECF Science Archive. The keywords PHOTFLAM (in ergs$^{-1}$ cm$^{-2}$ Å$^{-1}$) and EXPTIME (exposure duration) in the header of each image were used for converting instrumental magnitudes to flux densities and to Vega magnitudes based on the zero points given in the WFC2 data handbook (Baggett 2002). The broadband optical images ($u$, $g$, $r$, $i$, and $z$) were derived from the SDSS data archive (York et al. 2000; Stoughton et al. 2002). The background, fitted by a low-order Legendre polynomial, was subtracted from each band image after masking out all bright sources (Zheng et al. 1999; Wu et al. 2002). Then the counts were converted to flux densities and AB magnitudes. Figure 1 shows the three-color image of Arp 24 derived from the SDSS data archive. North is up, and east is to the left, as denoted by the crosshair, and the center is the region of the YSCC in this galaxy (see the text).

2.2. Infrared Images

Broadband mid-infrared images of Arp 24 were acquired with the Infrared Array Camera (IRAC; Fazio et al. 2004) and Multi-band Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) on board Spitzer. The basic calibrated data (BCD) were part of the Lockman Hole field in the Spitzer Wide-Area Infrared Extragalactic (SWIRE) Survey (Lonsdale et al. 2003). Following preliminary data reduction by the Spitzer Science Center pipeline, images of each of the four IRAC (3.6, 4.5, 5.8, and 8 μm) and MIPS 24 μm bands were mosaicked, after point-seeing refinement, distortion correction, and cosmic-ray removal (Fazio et al. 2004; Huang et al. 2004; Wu et al. 2005; Surace et al. 2005). The mosaicked images have pixel sizes of 0.6" and angular resolutions (full widths at half-maximum [FWHMs]) of 1.9", 2.0", 1.9", and 2.2" for the four IRAC bands, and a pixel size of 1.225" and a FWHM of 5.9" for the MIPS 24 μm band, respectively. Figure 2

![Three-color image of Arp 24 derived from the SDSS data archive.](http://www.sdss.org/dr5/algorithms/sdssUBVRITransform.html#Lupton2005)
shows Spitzer IRAC 3.6, 4.5, 5.8, and 8 µm and MIPS 24 µm band images of Arp 24. The continuum-subtracted Hα image was also plotted to emphasize the good correspondence of the peaks between Hα and 24 µm emissions.

2.3. Aperture Photometry

Aperture photometry was performed on the HST WFPC2 F300W and F814W images using 0.200 radius circular apertures. Photometry on SDSS, GALEX, Spitzer, and continuum-subtracted Hα images was performed using apertures of 12" and 120" diameters for individual regions and the entire galaxy, respectively. All photometric values were derived without aperture corrections. Both the IRAC and MIPS 24 µm bands have calibration uncertainties at the 10% level (Dale et al. 2005; Wu et al. 2005). The global values of the 70 and 160 µm fluxes of Arp 24 were derived from the catalogs of SWIRE data release 3 (Surace et al. 2005).

2.4. Optical Spectroscopy

The optical spectrum of the YSCC (see §3.2) in Arp 24 was taken on 2006 April 7. The observation was carried out with the 2.16 m telescope and the BFOSC. A G4 grism (from 4000 to 8000 Å) and a slit width of ~2" were used in this observation, giving a dispersion of roughly 200 Å mm⁻¹. A relatively higher resolution spectrum of this complex was taken on 2006 May 6 with the 2.16 m telescope and the OMR spectrograph. A 1200 line mm⁻¹ grating (from 6300 to 7100 Å), blazed at 6700 Å and with a slit width of 2", was used in this observation, giving a dispersion of about 50 Å mm⁻¹. An optical spectrum of the nuclear region in Arp 24 was taken on 2006 May 5 with the OMR spectrograph and a 300 line mm⁻¹ grating (from 3800 to 8000 Å) with a slit width of 2". The unprocessed frames were reduced with standard CCD procedures using IRAF. The CCD reductions include bias subtraction, flat-field correction, and cosmic-ray removal. The wavelength calibrations were carried out using Fe/Ar (for BFOSC) and He/Ne/Ar (for OMR) lamps. Kitt Peak National Observatory IRS standard stars were observed each night for flux calibrations.

3. RESULTS

3.1. Multiwavelength Emission in Arp 24

From SDSS (Fig. 1) and Spitzer (Fig. 2) images, we found that the nucleus of Arp 24 appears redder in optical and bright at 3.6 and 4.5 µm but is absent in the IRAC 8 µm and MIPS 24 µm bands. In the MIPS 24 µm image we identified four infrared-bright knots (labeled K0, K1, K2, and K3) in Arp 24, which are bluer in the optical and bright at 8 and 24 µm. The brightest infrared knot (K0) was found to be associated with a star-cluster complex based on HST images (see §3.2), so we relabeled it YSCC. Many gaseous structures and filaments were also shown in the IRAC 5.8 and 8 µm and MIPS 24 µm bands. Most of the emission at 8 µm (and also at 5.8 µm to a lesser extent) arises from the so-called aromatic features (usually attributed to PAHs) at 6.2, 7.7, and 8.6 µm in the photodissociation regions, which are often associated with the warm dust in or near star-forming regions (H II regions) and thus can be used as tracers of star formation (Peeters et al. 2004; Wu et al. 2005). The MIPS 24 µm emission, which is mainly due to hot dust emission from the VSGs, is also thought to be a good measure of the SFR of a galaxy (Wu et al. 2005; Calzetti et al. 2005; Pérez-González et al. 2006). Thus, we conclude that the four infrared-bright knots (YSCC, K1, K2, and K3) are dominated by young stars and are sites of active star formation. The Hα image of Arp 24 shows...
strong H$\alpha$ emission in these regions, which also indicates a young stellar population there (see Fig. 2).

The ultraviolet to infrared spectral energy distributions (SEDs) are shown in Figure 3 and Table 1. From comparison with the empirical SED templates generated using the GRASIL code (Silva et al. 1998; see also more detailed descriptions in Jarrett et al. 2006), we find that the YSCC, which has very strong 24 $\mu$m dust emission relative to PAHs, is very similar to the prototype starburst galaxy M82 (dotted line), and the IR knots are comparable to late-type Scd galaxy NGC 6946 (dashed line). Note that the flux densities of the IR knots have been divided by a factor of 10 ($10 \text{ dex}$) for clarity.

### Table 1: Spectral Energy Distributions

| Characteristics | YSCC | Nucleus | K1 | K2 | K3 | Total |
|-----------------|------|--------|----|----|----|-------|
| R.A. (J2000.0)  | 10 54 37.9 | 10 54 35.5 | 10 54 34.1 | 10 54 35.5 | 10 54 35.4 | 10 54 35.5 |
| Decl. (J2000.0) | +56 59 20 | +56 59 26 | +56 59 23 | +56 59 41 | +56 59 41 | +56 59 26 |
| FUV             | 0.77 | 0.49 | 0.23 | 0.30 | 0.28 | 7.59 |
| NUV             | 0.85 | 0.62 | 0.28 | 0.33 | 0.29 | 8.91 |
| $u$             | 1.21 | 1.30 | 0.48 | 0.57 | 0.50 | 14.30 |
| $g$             | 1.64 | 3.18 | 1.04 | 0.92 | 0.82 | 27.97 |
| $r$             | 1.92 | 4.36 | 1.43 | 1.22 | 1.10 | 36.21 |
| $i$             | 1.64 | 5.13 | 1.60 | 1.27 | 1.14 | 40.70 |
| $z$             | 1.71 | 5.67 | 1.73 | 1.32 | 1.17 | 43.76 |
| $J$             | ... | ... | ... | ... | ... | 52.0 |
| $H$             | ... | ... | ... | ... | ... | 55.4 |
| $K_s$           | ... | ... | ... | ... | ... | 38.0 |
| 3.6 $\mu$m      | 1.39 | 3.19 | 1.13 | 1.07 | 0.90 | 27.76 |
| 4.5 $\mu$m      | 0.99 | 1.92 | 0.70 | 0.70 | 0.57 | 16.96 |
| 5.8 $\mu$m      | 3.53 | 3.37 | 1.91 | 2.38 | 1.78 | 46.42 |
| 8 $\mu$m        | 9.13 | 6.79 | 4.42 | 5.85 | 4.33 | 106.66 |
| 24 $\mu$m       | 21.63 | 7.27 | 5.97 | 8.13 | 7.19 | 132.67 |
| 70 $\mu$m       | ... | ... | ... | ... | ... | 2326.96 |
| 160 $\mu$m      | ... | ... | ... | ... | ... | 4710.42 |
| H$\alpha$       | 40.26 | ... | 39.57 | 39.72 | 39.70 | 40.66 |

**Notes.** Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. The fluxes of the two GALEX bands (FUV and NUV), five SDSS bands ($u$, $g$, $r$, $i$, and $z$), three 2MASS bands ($J$, $H$, and $K_s$), four Spitzer IRAC bands (3.6, 4.5, 5.8, and $8 \mu$m), and three MIPS bands (24, 70, and 160 $\mu$m) are in units of mJy. The H$\alpha$-line luminosities are in units of log (ergs s$^{-1}$), after correcting the contamination of [N II] lines based on the [N II]/H$\alpha$ ratio derived from spectroscopy (see § 3.3).
is within a region of $\sim 0.95''$ radius (127 pc) in size and separated from the nuclear star cluster in the galaxy center by about 20.5'' ($\sim 2.7$ kpc). The measured fluxes and absolute magnitudes of the star clusters in the YSCC, the nucleus, and three other infrared-bright knots (K1, K2, and K3) are shown in Table 2. The different $m_{F300W} - m_{F814W}$ colors between clusters in each region primarily reflect the mean age of the stellar population.

The color-magnitude diagrams (CMDs) of the YSCC and three infrared-bright knots in Arp 24 are shown in Figure 5. The ages and masses of the clusters were estimated using Starburst99 instantaneous models (Leitherer et al. 1999), with a Salpeter initial mass function (IMF; $\alpha_{\text{IMF}} = 2.35$) between 0.1 and $120 \, M_\odot$ and metallicities $Z = 0.02$ and 0.008. The models are also shown in the CMDs; ages along the evolutionary lines that are drawn for cluster masses of $10^5$ (solid line) and $4 \times 10^4 \, M_\odot$ (dotted line) are indicated by diamonds ($Z = 0.02$) and plus signs ($Z = 0.008$) in $t = 1$ Myr intervals, beginning from 1 Myr on the left. The clusters in the YSCC and K1 have ages of around 3–5 Myr and masses of about $10^5 \, M_\odot$. The clusters in the other two infrared-bright regions (K2 and K3) are relatively less massive ($\sim 4 \times 10^4 \, M_\odot$) but have ages similar ($\sim 4–6$ Myr) to those in the YSCC and K1. The masses estimated here are consistent with those derived from $HST$ F300W/F814W luminosities and the mass-to-light ratio of $\sim 0.01–0.02$ in the visual band for young clusters with a $10^6$ burst (Chandar et al. 1999). The masses of the star clusters in the YSCC and K1 are consistent with those of YSCs or super star clusters (SSCs) (de Grijs 2003) observed in other interacting galaxies (e.g., IC 2163 and NGC 2207, Elmegreen et al. 2001; NGC 4038 and NGC 4039, Whitmore et al. 1999), which are thought to be the progenitors of luminous globular clusters (e.g., Ma et al. 2006a, 2006b; Kravtsov 2006).

3.3. Optical Spectroscopy

The optical spectrum of the nucleus in Arp 24 (Fig. 6) indicates a mixture of populations of different ages, with strong H$\beta$ absorption, which indicates the existence of a large number of evolved A-type stars (age $\sim 10^8$ yr; see, e.g., Wang & Wei 2006), and strong H$\alpha$ emission, which traces ongoing star formation. A template spectrum corresponds to an instantaneous-burst model with a young population of 100 Myr and metallicity $Z = 0.02$; an old population of 11 Gyr was also plotted for comparison. This result is in agreement with previous studies that the nuclear

![Image](image_url)

**FIG. 4.**—$HST$ WFPC2 F300W image of star clusters in the YSCC, the nucleus, and the three infrared-bright knots (K1, K2, and K3) in Arp 24. North is up, and east is to the left. The circles shown in the left image correspond to the 6'' radius apertures used in the SED studies (see § 3.2), and the ones shown in the right image correspond to 0.2'' radius apertures on the F300W image. [See the electronic edition of the Journal for a color version of the right panel of this figure.]

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### Table 2

| Cluster | Component | R.A. (J2000.0) | Decl. (J2000.0) | $F_{F300W}$ | $F_{F814W}$ | $m_{F300W}$ | $m_{F814W}$ | $m_{F300W} - m_{F814W}$ |
|---------|-----------|---------------|----------------|-----------|------------|------------|------------|---------------------|
| YSCC.... | 1         | 37.87         | 21.9           | 59.90     | 6.44       | -12.77     | -11.59     | -1.18               |
|         | 2         | 37.95         | 21.6           | 58.35     | 4.86       | -12.74     | -11.28     | -1.46               |
|         | 3         | 37.90         | 20.9           | 102.73    | 8.67       | -13.36     | -11.91     | -1.45               |
|         | 4         | 37.85         | 21.4           | 76.74     | 6.70       | -13.04     | -11.63     | -1.41               |
|         | 5         | 37.90         | 21.4           | 58.40     | 5.61       | -12.75     | -11.44     | -1.31               |
| Nucleus  | 1         | 35.54         | 26.4           | 41.02     | 26.42      | -12.36     | -13.12     | 0.76                |
| K1....... | 1         | 34.12         | 22.8           | 69.76     | 5.96       | -12.94     | -11.51     | -1.43               |
| K2....... | 1         | 35.68         | 41.9           | 28.27     | 2.92       | -11.96     | -10.73     | -1.23               |
| K3....... | 1         | 34.17         | 40.8           | 21.90     | 2.39       | -11.68     | -10.52     | -1.16               |
|         | 2         | 34.25         | 42.5           | 26.65     | 3.49       | -11.89     | -10.93     | -0.96               |
|         | 3         | 34.44         | 38.9           | 22.36     | 2.44       | -11.70     | -10.54     | -1.16               |

**Notes.**—Units of right ascension are seconds, preceded by $10^5 54''$, and units of declination are arcseconds, preceded by $+58^5 59''$. The fluxes ($F_{F300W}$ and $F_{F814W}$) are in units of $10^{-18}$ ergs$^{-1}$ cm$^{-2}$ Å$^{-1}$, and the magnitudes ($m_{F300W}$ and $m_{F814W}$) are in the Vega magnitude system.
clusters are massive and dense star clusters, which formed stars recurrently until the present day (Walcher et al. 2005, 2006). Unfortunately, its HST STIS spectra, which can provide better separation of nuclear star-cluster light from underlying galaxy light than our ground-based spectrum, cannot be used for stellar population analysis (due to its low signal-to-noise ratio, ~2.9; see Rossa et al. 2006).

The optical spectrum of the YSCC in Arp 24 (Fig. 7) shows strong hydrogen and oxygen emission lines, which indicate young stellar populations and active star formation. The derived redshift is 0.007, matching the redshift (0.0069) of the galaxy derived from the Updated Zwicky Catalog (Falco et al. 1999). The emission lines were fitted with Gaussian profiles, and the line fluxes are listed in Table 3. The line ratios are Hα/Hβ = 3.13, [O III]/Hβ = 3.57, [N II]/Hα = 0.12, and [S II]/Hα = 0.19. Using standard optical line ratio diagnostic diagrams and comparing with the Mappings III code (Kewley et al. 2001; Kewley & Dopita 2002) results, we computed photoionization models and estimated the ionization parameter q of the YSCC, which is about 4 x 10^7 cm s^{-1}.

The dust extinction can be estimated from the Balmer decrement (Calzetti 2001),

\[ E(B-V) = 2.5 \log \left( \frac{\text{H} \alpha / \text{H} \beta}{\text{H} \alpha / \text{H} \beta_0} \right) \frac{k(\text{H} \beta) - k(\text{H} \alpha)}{k(\text{H} \beta)}, \]

where the value of the intrinsic luminosity ratio Hα/Hβ is 2.87 for temperature T = 10,000 K and case B recombination.

### Table 3

| Line     | \( \lambda_0 \) (Å) | Flux (10^{-15} ergs cm^{-2} s^{-1}) | Spectrum     |
|----------|---------------------|------------------------------------|--------------|
| Hβ       | 4861                | 67.0 ± 1.0                         | Low resolution |
| [O II]   | 3727                | 63.4 ± 1.0                         | Low resolution |
| [O II]   | 3731                | 5042                               | Low resolution |
| Hα       | 6563                | 210.0 ± 2.0                        | High resolution |
| [N II]   | 6583                | 6629                               | High resolution |
| [S II]   | 6718                | 6765                               | High resolution |
| [S II]   | 6733                | 6780                               | High resolution |

Notes.—The line fluxes of the high-resolution spectrum have been scaled to the low-resolution one using Hα-line fluxes. This correction does not greatly affect the line ratios used in § 3.3.
(Osterbrock 1989), and the value of the differential extinction $k(H \beta) - k(H \alpha)$ between H$\alpha$ and H$\beta$ is 1.163 (Calzetti 2001). Then the extinction of the YSCC can be calculated from $A_V = R_V E(B - V)$ (where $R_V = 3.1$); the value is about 0.25. It is smaller than the attenuations in M81 ($A_V \sim 0.5$; see, e.g., Hill et al. 1995), M51 ($A_V \sim 3$; see Calzetti et al. 2005), and the archetypal starburst galaxy M82 ($A_V \sim 0.5$; Mayya et al. 2006).

The metallicity was estimated using the line ratios, following Vacca & Conti (1992),

$$\log (O/H) = -0.69 \log R_3 - 3.24,$$

where $-0.6 \leq \log R_3 \leq 1.0$ and

$$R_3 = \frac{I([O \, iii] \lambda 4959) + I([O \, iii] \lambda 5007)}{I(H \beta)}.$$

The measured metallicity $[12 + \log (O/H)]$ of the YSCC is about 8.37, or 0.51 $Z_\odot$ if the value of 8.66 for solar abundance (Asplund et al. 2004) is adopted. This relation [$R_3 \sim \log (O/H)$] has been shown to be affected by the ionizing photon hardness. Thus, we also estimated metallicities using the $[N \, ii]/H \alpha$ ratio for a comparison, with

$$12 + \log (O/H) = 9.12 + 0.73 \log \frac{[N \, ii]}{H \alpha}$$

(Kewley & Dopita 2002). The metallicity of the YSCC estimated using this relation is about 8.45, consistent with that derived from the $R_3$ value. The metallicity of the nucleus in Arp 24 was also estimated using the $[N \, ii]/H \alpha$ ratio, and the value is about 8.79, much higher than that of the YSCC.

### 3.4. Star Formation Rate and Stellar Mass

The total SFR of Arp 24 was calculated using infrared luminosity derived from Spitzer MIPS (24, 70, and 160 $\mu$m) and the equation of Dale & Helou (2002),

$$L_{\text{TIR}} = 1.559 \nu L_{24} + 0.768 \nu L_{70} + 1.347 \nu L_{160}.$$

Then SFR$_{\text{total}}$ can be estimated by multiplying $L_{\text{IR}}$ (in ergs s$^{-1}$) by a conversion factor of $4.5 \times 10^{-44} M_\odot$ yr$^{-1}$ (Kennicutt 1998)$^8$. The total SFR in Arp 24 is about 1.05 $M_\odot$ yr$^{-1}$. The SFRs of the YSCC and K1, K2, and K3 were estimated using 24 $\mu$m dust emission, which is thought to be a good measure of the SFR of a galaxy (Wu et al. 2005; Calzetti et al. 2005; Pérez-González et al. 2006), and equation (3) of Wu et al. (2005),

$$\text{SFR}_{24 \mu m} (M_\odot \text{yr}^{-1}) = \frac{\nu L_{24}(\mu m)}{6.43 \times 10^8 L_\odot}.$$

The measured SFRs in the regions of the YSCC, K1, K2, and K3 are about 0.10, 0.03, 0.04, and 0.03 $M_\odot$ yr$^{-1}$, respectively. The SFR in YSCC is extremely high, considering its relatively small spatial size compared with the entire galaxy. The SFR per unit area of this complex was estimated to be 0.05–1.97 $M_\odot$ yr$^{-1}$ kpc$^{-2}$ using the 24 $\mu$m 6$''$ radius and the $HST$ 0.95$''$ radius, respectively. It is comparable to or even much stronger than the definition of a starburst galaxy ($\sim 0.1 M_\odot$ yr$^{-1}$ kpc$^{-2}$; Kennicutt et al. 2005); thus, the YSCC can be classified as a localized starburst (Efremov 2004).

Although using infrared emission to estimate SFRs is more indirect than other young star tracers such as UV and H$\alpha$-line emissions, it suffers relatively minor extinction effects that are difficult to correct. From the simulations of the performance of star formation indicators in the presence of dust, Jonsson (2004) found that the infrared luminosity is more reliable than H$\alpha$ and FUV luminosities, which suffer severely from dust attenuation, and the situation can only partially be remedied by dust corrections. For comparison we calculated the SFRs based on H$\alpha$-line and FUV luminosities using the relations $SFR_{H\alpha} (M_\odot \text{yr}^{-1}) = 7.9 \times 10^{-22} L_{H\alpha} (\text{ergs s}^{-1})$ (Kennicutt 1998) and $SFR_{\text{FUV}} (M_\odot \text{yr}^{-1}) = \log L_{\text{FUV}} (L_\odot) - 9.51$ (Iglesias-Paparo et al. 2006). The SFR$_{H\alpha}$ and SFR$_{\text{FUV}}$ (not reddening corrected) for each region are about 0.14, 0.03, 0.04, and 0.04 $M_\odot$ yr$^{-1}$, respectively, a bit higher than that derived from the 24 $\mu$m luminosities. A better way for estimating SFRs may be based on a combination of the observed infrared and ultraviolet/optical luminosities, as suggested recently by some authors (e.g., Kennicutt 2007; Iglesias-Paparo et al. 2006). We adopted the relations

$$\text{SFR} (M_\odot \text{yr}^{-1}) = 4.5L_{\text{TIR}} + 7.1L_{\text{FUV}} (10^{17} \text{ W})$$

(Dale et al. 2007) and

$$\log L(\text{TIR}) = \log L(24) + 0.908 + 0.793 \log [L_{\nu}(8)/L_{\nu}(24)]$$

(Calzetti et al. 2005). The SFR$_{\text{IR}+\text{FUV}}$ values for each region are then about 0.14, 0.05, 0.07, and 0.06 $M_\odot$ yr$^{-1}$, respectively, slightly higher than previous estimates. Due to the relatively small variations in SFRs derived from different SFR indicators, we adopted the values of SFR$_{24 \mu m}$ for further analysis.

The stellar masses for the old stellar population in different regions of Arp 24 were estimated based on SDSS photometry following Bell et al. (2003),

$$\log (m_r/M_\odot) = -0.4(M_{AB} - 4.67) + [(a_r + b_r)(g - r)]_{AB} + 0.15,$$

where the coefficients $a_r$ (−0.306) and $b_r$ (0.097) are taken from Table 7 of Bell et al. (2003). The estimated stellar masses in the regions of the YSCC, K1, K2, and K3 are about $10^{8.5}, 10^{8.6}, 10^{8.5}$, and $10^{8.4} M_\odot$, respectively. We also compared the measured stellar masses with the monochromatic IRAC 3.6 $\mu$m luminosities (which are around $10.57 \times 10^{40}, 8.55 \times 10^{40}, 8.10 \times 10^{40}$, and $6.81 \times 10^{40}$ ergs s$^{-1}$, respectively), which are thought to be approximate measures of the stellar masses in galaxies (e.g., Smith et al. 2007). We found that the regions in Arp 24 followed a scaling relation between $m_{15} (\text{mass})$ and $\log L(3.6 \mu m)$ similar to that in the Arp 82 system (Hancock et al. 2006). The specific star formation rate (SSFR, SFR per unit stellar mass, in units of Gyr$^{-1}$) for each region is 0.32, 0.08, 0.14, and 0.13 Gyr$^{-1}$. The SSFRs of these regions in Arp 24 are higher than those of most of the local star-forming galaxies (with values between 0.03 and 0.2 Gyr$^{-1}$; Bell et al. 2005), but are much lower than that of luminous infrared galaxies in the local universe (lying between 1.2 and 10 Gyr$^{-1}$; Wang et al. 2006). However, the SSFRs estimated here will only be a lower limit for the SSFRs
within or around the YSCs in themselves, due to the contamination of starlight (dominated by the old population) from their parent galaxy.

4. DISCUSSION

4.1. Possible Formation Scenarios of the YSCs in Arp 24

“Peculiar one-time events and special places that have extraordinarily high energy inputs” was suggested by Elmegreen (2004) as one of the possible mechanisms for triggering the formation of YSCs. He suggested that YSCs in galaxies undergoing interactions may have formed by large-scale or local shock compressions and collapse from cloud impacts or colliding supernovae. Bastian et al. (2006a) studied the YSC complexes in the Antennae galaxies and suggested that if we assume that the grouping of complexes formed out of the same GMC, then the star formation is triggered by an external perturbation. Cannon et al. (2005) studied the infrared properties of the supergiant shell region of the dwarf galaxy IC 2574 using Spitzer and demonstrated that the expanding shell is affecting its surroundings by triggering star formation and heating the dust. The morphology of Arp 24 indicates that it may have formed in a minor merger scenario (interaction between a gas-rich late-type spiral and a small companion) or from cosmological accretion of gas on galactic disks (Bournaud et al. 2005). Shaping/reshaping of galaxies is the biggest effect generally attributed to mergers (Cox 2004). The tidal stripping of a satellite can produce features such as long tails, and the accretion introduces new stellar populations into the galactic disk (Walker et al. 1996); i.e., it promotes a high SFR (e.g., Mihos & Hernquist 1994, 1996; see also Cox 2004) in Arp 24. The YSCs may form as a consequence of the high SFR per unit area in the galaxy (Larsen & Richtler 2000). Arp 24 shows a strong asymmetry in $g - i$ colors (see Fig. 8) through the galactic disk; the regions near the YSCC are relatively bluer than those near the nucleus. This asymmetry may be due to the differences in star formation, stellar populations, or gas/dust contents of different regions caused by galaxy interactions. Furthermore, the one-armed appearance and the broad fanlike structure seen in the primary disk of Arp 24 indicate that this galaxy may have formed in a retrograde flyby encounter (see, e.g., Barnes & Hernquist [1996], Struck & Smith [2003], a review by Struck [1999], and references therein).

The companion galaxy in the east seems nearly edge-on (and also a bit warped), with a weak bridge connecting to the primary disk and faint knots near the outer edges of its disk (see Figs. 1 and 2). This could indicate the existence of an edge-on ring (or other waves), which would be consistent with a small angle between the orbital plane of the companion and the disk plane of the primary, if the closest approach was on the west side. It is also possible that the primary disk might have rotated by about half a turn in the time since the closest approach. Thus, the region of the YSCC in Arp 24 might be in the part of the disk that was closest to the companion and most perturbed at that time. If we adopt a rotation velocity of about 100 km s$^{-1}$ (derived from the rotation curve of M51) and the distance between YSCC and the nuclear star cluster ($\sim$2.7 kpc) as the radius of rotation, then such a half-turn will take about 8 $\times$ 10$^7$ yr; moreover, if we assume a circular orbit for the encounter and a relative velocity of $\sim$400 km s$^{-1}$ between the companion and the primary’s core (Eneev et al. 1973), then the time since the closest approach in the west is roughly about 10$^8$ yr, consistent with the rotational time estimated above. This timescale may be linked to the processes of YSCC formation (e.g., modes and mechanisms of the induced star formation; feedbacks including radiation/thermal pressure, stellar winds, and supernova blasts). The existence of a large amount of young (A-type) stars in the nucleus of Arp 24 (see § 3.3) may also be related to the age of interaction in this system. However, such a formation scenario still remains speculative and needs to be confirmed by hydrodynamic modeling (e.g., Struck et al. 2005) and numerical simulations of star formation in galaxy mergers (e.g., Struck & Smith 2003; Cox 2004).

Recent studies have shown that young star clusters tend to form in large complexes instead of isolation (Bastian et al. 2005). According to Efremov (2004), these complexes (or so-called clusters of clusters) are often the massive bound clusters formed from a single gas supercloud within high-pressure surroundings. Zhang et al. (2001) made a multiwavelength study of the mass, age, and space distributions of young star clusters in the Antennae galaxies (NGC 4038 and NGC 4039) and found that the young clusters have a clumpy space distribution and are located in regions of high interstellar density. The cluster formation rate ($\Sigma_{\text{CFR}}$) is correlated with the interstellar medium density ($\Sigma_{\text{ISM}}$). From the spectroscopic studies of an unusual star complex in NGC 6946 (Larsen et al. 2002) using the Special Astrophysical Observatory 6 m and Keck 10 m telescopes, Efremov et al. (2002) found that this complex resembles a circular bubble 600 pc in diameter with a young SSC near its center. The intensities of the emission lines within and around the complex indicate that shock excitation makes a significant contribution to the emission from the most energetic region. Larsen (2004b) found a strong correlation between cluster age and “crowding” of the environment, with most of the crowded clusters having young ages ($\leq$10$^7$ yr). Chen et al. (2005) found a tight group of clusters in the very luminous giant H II region NGC 5461 in the spiral galaxy M101. Bastian et al. (2005) found several YSCs that had formed in larger groupings/complexes in spiral galaxy M51. These complexes all are young (<10 Myr), have sizes between 85 and 240 pc, and have masses of (3–30) $\times$ 10$^4$ $M_\odot$, similar to the YSCC in Arp 24.

Elmegreen et al. (1993) suggested that the local turbulent velocity dispersion plays an important role in setting the mass scale of the star-forming clouds. The larger mass clouds, which formed in more turbulent conditions, are more resistant to the disruptive effects of young stars; i.e., they can sustain a higher star-forming efficiency. Clark et al. (2005) investigated the formation of star clusters in unbound GMCs, where the cloud tends to form

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8 Derived from the Fabry-Pérot de Nouvelle Technologie pour l’Observatoire du Mont Mégeantic (FaNTOmM); see Daigle et al. (2006).
a series of star clusters and disperse quickly within a rapid star formation process (~10 Myr). They also proposed that the clusters that form in the unbound GMCs may be progenitors of the OB associations. Zhang et al. (2001) found that the youngest star clusters in the Antennae galaxies are associated with molecular cloud complexes with characteristic radii of about 1 kpc. Wilson et al. (2003) studied properties of the supergiant molecular complexes in the Antennae using CO emission and suggested that young massive star clusters formed from dense cores within the observed supergiant molecular complexes. The star clusters in the YSCC of Arp 24 may have formed in a single GMC simultaneously, since they have similar ages and masses and reside in a small region of ~127 pc (see § 3.2). They may then have dispersed quickly and dissipated to become the field population before reaching ages of 100 Myr, according to Wilson et al. (2006). However, this scenario still needs to be confirmed by deep spectroscopic observations with high dispersion and high spatial resolution to measure the velocity dispersions and obtain chemical abundances of individual clusters in the YSCC (see, e.g., Larsen et al. 2006; Bastian et al. 2006b). There is no evidence of merging of star clusters in the center of the YSCC, which was found in many complexes in M51 (Bastian et al. 2005).

Alternatively, perhaps the YSCC is a dwarf galaxy that fell into Arp 24 previously during a merger event. Its blue color ($g - i = -0.84$; see also Fig. 8) is similar to those of irregular galaxies (Fukugita et al. 1995), and its absolute magnitude ($M_g = -13$) is located at the faint end of the luminosity function of extremely low-luminosity galaxies (Blanton et al. 2005). Its metallicity is low (see § 3.3) and is comparable to those of local dwarf irregular galaxies (e.g., NGC 6822; Lee et al. 2006). Its warm infrared color (high $F_{24 \mu m}/F_{8 \mu m}$ ratio; see § 4.2) is also consistent with that of irregular galaxies (e.g., DDO 53) in the Spitzer Infrared Nearby Galaxies Survey (Kennicutt et al. 2003; Dale et al. 2005).

**4.2. PAH and Warm Dust Emission**

From the analysis of SEDs of the YSCs in Arp 24 (see § 3.1), we find that the YSCC has higher 24 $\mu m$ emission relative to the starlight (3.6 $\mu m$) and PAH emission (8 $\mu m$) than the nucleus and other infrared-bright knots (Fig. 9). Regions associated with YSCs (or SSCs) often show “warm” infrared colors (high 24 $\mu m$ emission relative to that at shorter wavelengths) in several interacting and starburst galaxies. Thuan et al. (1997) discovered six SSCs with ages $\leq$25 Myr and within a region $\sim$520 pc in diameter in the extremely metal-poor ($Z 
\sim Z_{\odot}/41$) blue compact dwarf galaxy (BCD) SBS 0335–052. Mid-infrared spectra from ISO and Spitzer show no sign of PAH emission and a relatively flat continuum between 5 and 20 $\mu m$ (Thuan et al. 1999; Houck et al. 2004), which can be explained by the destruction of the PAH molecules by the high UV radiation field. Jarrett et al. (2006) found the that tidal-tail supermassive star clusters (with $M \sim 10^6 M_\odot$) in the Tadpole galaxy (UGC 10214) have exceptionally strong 24 $\mu m$ emission relative to the starlight, hot dust continuum, and PAH emission. Elmegreen et al. (2006) studied the infrared clump emissions in the interacting galaxy pair IC 2163 and NGC 2207 and found that the brightest giant infrared clump (feature i), which contains two SSCs, numerous other star clusters and associations, several dark dust clouds, and supernova 1999ee, has extremely high 24 $\mu m$ emission relative to 3.6 $\mu m$ and 8 $\mu m$ emission. They suggested that this giant clump may have formed by gravitational instabilities in the compressed gas of the oval and spiral arms. In the western spiral arm of the well-studied nearby spiral galaxy M51 (NGC 5194), several star-forming regions are associated with luminous YSCs and show high $F_{24 \mu m}/F_{8 \mu m}$ ratios (e.g., region 05-01 shown in Calzetti et al. [2005], associated with YSC 180 shown in Larsen [2000]; see Fig. 9). Special conditions in these infrared-warm regions can lead to the formation of extremely young and massive star clusters, with strong UV radiation fields that can reduce the PAH feature strength and enhance the warm dust emission.

The high $F_{24 \mu m}/F_{8 \mu m}$ ratio in the YSCC may be due to the weakness or lack of the PAH emission bands, which are caused by the low PAH abundance as a consequence of PAH destruction by a strong UV radiation field and/or other mechanisms (e.g., shocks) within this region, or “PAH-dust competition,” i.e., the condition that PAH molecules cannot be excited by UV photons due to the presence of the dust grains (Martin-Hernandez et al. 2006). The elevation of the 24 $\mu m$ dust emission indicates that the VSGs have been heated to a high temperature by the nearby luminous young stars. The hardness of the interstellar radiation field may play a major role in the destruction of PAHs in the center of star formation regions (e.g., Madden et al. 2006; Bendo et al. 2006) and cause the warm infrared colors. The very blue optical color of the YSCC region in Arp 24 (see § 3.1) indicates that shocks induced by strong stellar winds and/or supernova explosions could also be a mechanism for destroying PAHs (O’Halloran et al. 2006). Low PAH abundance can also originate from low PAH formation rates due to different dust formation processes in a low-metallicity environment (e.g., Hogg et al. 2005; Engelbracht et al. 2005). Gordon et al. (2006) found that the 6.2 and 7.8 $+ 8.6 \mu m$ PAH features in M101 H II regions are weak or absent at a metallicity $12 + \log (O/H) \sim 7.5$. Thus, the low O/H abundance in the region of the YSCC compared with that in the nuclear region (see § 3.3) indicates that metallicity may play a role in setting infrared colors in Arp 24. However, Bolatto et al. (2007) showed that the $F_{24 \mu m}/F_{8 \mu m}$ ratios of the regions in the Small Magellanic Cloud (SMC) are regulated primarily by the local interstellar radiation field rather than metallicity, and suggested that photodestruction of PAHs may be primarily responsible for the variation of the measured $F_{24 \mu m}/F_{8 \mu m}$ ratios in the SMC. Dust can be heated by emission arising from older and cooler stars (e.g., B stars; Peeters et al. 2004), besides ionizing photons from young hot stars. The strength of the 24 $\mu m$ continuum emission from VSGs is more sensitive to the radiation energy density and hardness than the 8 $\mu m$ PAHs (Roussel et al.
Thus, the $F_{\lambda, \mu m}/F_{24, \mu m}$ ratio could also be linked to the mean age of the stellar populations responsible for dust excitation.

Regions associated with YSCs do not always show warm infrared colors. Cannon et al. (2006a) found a lower $F_{24, \mu m}/F_{8, \mu m}$ ratio and modest warm dust emission of the SSC in the center of nearby dwarf starburst galaxy NGC 1705. They suggested that this may be due to the dust removal by multiphase outflow, or evacuation by high UV flux from the SSC. The K1 region in Arp 24, which is also associated with a young ($t \sim 3–5$ Myr) massive ($M \sim 10^3 M_\odot$) star cluster, does not show a high $F_{24, \mu m}/F_{8, \mu m}$ ratio like that of the YSCC. This indicates that the region-to-region variations of mid-infrared colors may depend on several physical parameters such as dust composition, dust temperature, and PAH molecular abundance. On the other hand, not all regions with warm infrared colors are associated with optically bright YSCs. For example, in NGC 4038 and NGC 4039, the brightest knot in the 15 $\mu m$ map (Mirabel et al. 1998) has only a faint $J$-band counterpart (object 80; Whitmore & Schweizer 1995), but was found to be associated with a molecular complex (SGMC 4–5; Wilson et al. 2000). We found that this knot has infrared colors even warmer than that of the YSCC in Arp 24, based on archival Spitzer data (PI: G. Fazio; see also Wang et al. 2004). Its very red near-infrared color ($J – K_s = 1.86$) indicates that it suffers from heavy dust extinction (Brandl et al. 2005). Thus, we speculate that some star clusters in galaxies that are very young and optically faint due to heavy dust extinction may also have warm infrared colors like the YSCC that we found in Arp 24. This may also be caused by the strong UV radiation fields in these regions, which may destroy the PAH molecules and enhance the VSG emission at 24 $\mu m$.

Firm conclusions must await a quantitative multiwavelength analysis of a large, well-defined, and unbiased sample of YSCs in galaxies. The precise roles of the PAH destruction and the enhanced 24 $\mu m$ dust emission in setting the $F_{24, \mu m}/F_{8, \mu m}$ ratios of the YSCs in Arp 24 could be well determined by using infrared spectroscopic observations. Ground-based mid-infrared imaging and spectroscopy of YSCs with high spatial resolution (subarcsecond; e.g., Snijders et al. 2006) will aid in studying the spatial distributions and origins of PAH and warm dust emissions.

5. SUMMARY

In this work we present a study of young massive clusters in the interacting galaxy Arp 24 using images from HST, Spitzer, SDSS, GALEX, Hα imaging, and optical spectroscopy. Our major findings are the following.

1. From the HST WFPC2 $U$- and $I$-band images, we found that the brightest infrared knot in Arp 24 is associated with a complex of young massive star clusters (the YSCC). The ages and masses of the star clusters in the YSCC and the other three infrared-bright knots (K1, K2, and K3) were estimated using HST color-magnitude diagrams and comparing with the Starburst99 synthesis models. The clusters in the YSCC and K1 region are very young (within ages of 3–5 Myr) and massive ($M \sim 10^3 M_\odot$), while the clusters in the K2 and K3 regions are relatively less massive ($M \sim 4 \times 10^2 M_\odot$) but have ages similar ($\sim 4–6$ Myr) to those in the YSCC and K1 regions. The masses of the star clusters in the YSCC and K1 are consistent with those of young massive star clusters or SSCs observed in other interacting galaxies.

2. Using standard optical emission-line ratio diagnostic diagrams and comparing with the Mappings III code results, we computed photoionization models and estimated the ionization parameter of the YSCC. The metallicity of the YSCC was estimated using emission-line ratios, and the star formation rates of the YSCC and K1, K2, and K3 regions were calculated using monochromatic 24 $\mu m$, FUV, and Hα-line luminosities. The SFR density of the region of the YSCC is high and comparable to or even much stronger than the definition of a starburst galaxy. The stellar masses for the old stellar populations in different regions were estimated based on SDSS photometry and IRAC 3.6 $\mu m$ luminosities.

3. We speculate that the formation of the YSCs in Arp 24 is triggered by galaxy interaction, and that this galaxy may have been formed by a retrograde flyby encounter, indicated by its one-armed appearance and fanlike structure. The clusters in the YSCC may have formed in a single giant molecular cloud simultaneously, since they have similar ages and masses and reside in a small region of $\sim 127$ pc.

4. From the ultraviolet to mid-infrared spectral energy distributions, we found that the region of the YSCC is relatively bluer in optical and has higher 24 $\mu m$ dust emission relative to the emission at 8 $\mu m$. We speculate that this is primarily due to a strong UV radiation field (or shocks) within this region that may destroy the PAHs and enhance the VSGs’ emission at 24 $\mu m$. However, firm conclusions must await a well-defined sample and upcoming infrared spectroscopic observations.

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