Star Formation Histories within the Antennae Galaxies (Arp 244)

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ABSTRACT

With the imagery from \textit{GALEX}, \textit{HST}, 2\textit{MASS}, and \textit{Spitzer}, and at the resolution of MIPS 24 µm (∼6″), we study the variations of the broadband spectral energy distributions (SEDs) of star-forming regions within the nearest prototypical major merger — the Antennae galaxies. By including MIPS 24 µm dust emission into stellar population analysis, we reliably, albeit roughly, constrain the star formation histories of these 24 µm selected star-forming regions across the merging disks of the Antennae. Our population analysis is consistent with the star formation scenario that, most regions across the whole system are at a modest level of star formation with the exception of some localized intense starburst sites in the well-known overlap regions and the western-loop regions of northern galaxy NGC 4038. Compared with all the other regions, the young overlap regions currently (<10 Myr) are experiencing much more violent enhancement of star formation. Across the overlap regions, we suggest two sequential star formation paths which we interpret as the imprints of the inter-penetrating process of the two merging disks following their second close encounter. And we suggest that the star formation in the southern and (especially) northwestern edges of the overlap zone may have been just triggered by pre-starburst shocks. The well-known mid-infrared "hotspot" in the overlap regions is also a "hotspot" at 4.5 µm, whose total 4.5 µm emission (≥80% from both hot dust and atomic/molecular lines) is comparable with that of the two galactic nuclei.

Key words: galaxies: individual (the “Antennae” galaxies) – galaxies: interactions – galaxies: stellar content – galaxies: starburst – galaxies: photometry

1 INTRODUCTION

Galaxy mergers, especially major mergers, can dramatically influence the morphological and star-forming properties of galaxies over relatively short timescales. Almost all the ultraluminous infrared galaxies (ULIRGs) — the strongest starbursts in the local Universe, are in interacting/merging systems (Sanders & Mirabel 1996). Moreover, Conselice, Chapman & Windhorst (2003) suggested that about two thirds of submillimeter galaxies at z > 1 are undergoing major mergers. Galaxy interactions/mergers seem to be very frequent in the past (e.g. Le Fèvre et al. 2000; Peeters et al. 2002; Conselice et al. 2003; Elbaz & Cesarsky 2003; Kurultepe et al. 2007; de Ravel et al. 2008; Lin et al. 2008; Conselice, Yang & Bluck 2009). Therefore, it is of great importance to understand how the burst of star formation is triggered in the course of interacting/merging.

At a distance of 19.2 Mpc (H₀ = 75 km s\(^{-1}\) Mpc\(^{-1}\))\textsuperscript{1}, the Antennae (NGC 4038/39, Arp 244) is the nearest prototypical major merger between two gas-rich spiral galaxies (Toomre & Toomre 1972; Hibbard et al. 2001). Thus it provides us with a unique opportunity to study the induced star formation process as a consequence of interaction in detail. It has been extensively studied at essentially all wavelengths from X-ray to radio (Hummel & van der Hulst 1984).

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\footnote{1 We note the recent debate about the distance to the Antennae. Saviane et al. (2008) determined a distance of ∼13.3 Mpc from the tip of red giant branch, whereas Schweizer et al. (2008) estimated a distance of ∼22.3 Mpc based on the type Ia supernovae 2007es light curve. Throughout this work, we assumed the traditionally adopted Hubble Flow distance. However, our conclusions are not affected by the controversy over the distance.}
Read, Ponman & Wolstencraft 1993; Vigroux et al. 1996; Meece et al. 1998; Whitmore et al. 1999; Neff & Ulvestad 2000; Wilson et al. 2001; Fabbiano, Zezas & Murray 2001; Gao et al. 2001; Hibbard et al. 2001; Fabbiano et al. 2003; Fabbiano et al. 2004; Wang et al. 2004; Mengel et al. 2005; Bastian et al. 2006; Gilbert & Graham 2007; Schulz et al. 2007; Brandl et al. 2008. ISO mid-infrared (MIR) observations (Mirabel et al. 1998) show that the most intense starburst in this system takes place in the so-called overlap region between the two nuclei, which indicates its intermediate merging stage, almost totally obscured in the optical. Considering the abundant molecular gas, wide spread star formation and overall modest star formation efficiency, Gao et al. (2001) argued that Arp 244 has the potential of producing an ultrasublime starburst in a late stage of merging.

In the Antennae, observations with HST have identified thousands of super star clusters (SSCs) (Whitmore et al. 1999), possibly being formed as part of the merging process. Both theoretical predictions (Goodwin & Bastian 2006) and observations (Whitmore 2004; Fall, Chandar & Whitmore 2004; Mengel et al. 2005; Bastian et al. 2006; Gilbert & Graham 2007; Schulz et al. 2007; Brandl et al. 2008). ISO mid-infrared (MIR) observations (Mirabel et al. 1998) show that the most intense starburst in this system takes place in the so-called overlap region between the two nuclei, which indicates to the intermediate merging stage, almost totally obscured in the optical. Considering the abundant molecular gas, widespread star formation and overall modest star formation efficiency, Gao et al. (2001) suggested that Arp 244 has the potential of producing an ultrasublime starburst in a later stage of merging.

Evolutionary population synthesis has become a powerful tool of interpretation of the integrated spectrophotometric observations of galaxies and sub-galactic regions. The most common method of model-observation comparison for stellar population analysis in galaxies is SED-fitting, with either least-squares or chi-squared minimization technique (e.g. Kong et al. 2004; Gavazzi et al. 2002). However, the well-known age-extinction degeneracy problem prevents us from obtaining reliable information about the star formation history for these galaxies or their sub-galactic regions, especially when only broadband photometry data are available. This is because these extended regions have an unknown mixture of various stellar populations, and the different populations may experience totally different star formation histories (Calzetti, Kinney & Storchi-Bergmann 1994; Charlot & Fall 2000).

With the inclusion of the high-quality and high resolution Spitzer 24 µm dust emission data in our population analysis, we show here that the degeneracy between stellar population and dust extinction can be broken to a great extent. Thus, for the first time, we can reliably, albeit roughly, constrain the star formation histories within the Antennae galaxies using SEDs over the whole spectral range from far-UV (FUV) to MIR. The outline of this paper is the follow-

ing: In Sect. 2 we introduce the multi-band data that we use in this study, and give the multiwavelength photometry of star-forming regions selected mainly from the 24 µm image. Sect. 3 gives some brief comparisons of the broadband SEDs and their variations across the whole system. Sect. 4 presents our methodology to constrain the star formation histories across the merging disks, and the main results of our population analysis. We discuss these results in Sect. 5 and then a summary of our main findings follows in Sect. 6.

## 2 DATA AND PHOTOMETRY

### 2.1 Data

Both FUV (∼1516 Å) and near-UV (NUV; ∼2267 Å) images were derived from the GALEX Ultraviolet Atlas of Nearby Galaxies distributed by Gil de Paz et al. (2007). The FWHMs of the PSFs are 5′′ and 6′′ at FUV and NUV, respectively. With these data, Hibbard et al. (2003) have studied the stellar populations of the famous tidal regions.

Four broadband (F336W, F439W, F555W, F814W) and one narrowband (F658N; Hα) images (Whitmore et al. 1999) taken with the WFPC2 aboard the HST were obtained as B associations from the MAST Archive, and mosaic containing the four chips for each image was created.

NIR JHKs atlas images from 2MASS were retrieved through the Interactive 2MASS Image Service.

The Spitzer imagery (3.6, 4.5, 5.8, 8.0, 24.0 µm) of the Antennae was obtained with both the Infrared Array Camera (IRAC; Fazio et al. 2004) and the Multiband Imaging Photometer for Spitzer (MIPS; Rieke et al. 2004) on board the Spitzer Space Telescope. The Basic Calibrated Data (BCDs) were retrieved with the Leopard software. Background matching, cosmic-ray removal, flat-fielding and mosaicking were performed using the Spitzer Science Center’s reduction software package MOPEX. Images of the four IRAC bands have previously been presented by Wang et al. (2004).

### 2.2 Region Selection and Photometry Extraction

Prior to our multiwavelength photometry comparison and extraction, all images were background removed, registered/aligned, and resampled to the same pixel scale (1.5′′). Then all images (except FUV/NUV) are convolved to the same resolution of MIPS 24 µm with the convolution kernels provided by Gordon et al. (2008).

We select star-forming regions primarily as 24 µm emission peaks, since 24 µm has been shown to be a very good local tracer of current star formation (e.g. Calzetti et al. 2003). Practically, we first use the IRAF DAOFIND task in DAOPHOT stellar photometry package (Stetson 1987).

2 http://archive.stsci.edu/hst/wfpc2/search.html
3 http://irsa.ipac.caltech.edu/applications/2MASS/IM/interactive.html
4 Available at http://ssc.spitzer.caltech.edu/postbcd/download-mopex.html
5 http://ssc.spitzer.caltech.edu/propkit/sport/
6 IRAF is distributed by the National Optical Astronomy Observatories which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
to find all local emission enhancements with 10 σ signal-to-noise (S/N) ratio threshold in the 24 μm image. Then we examine the findings of local enhancements visually and check carefully to ensure that these previously detected enhancements are true star-forming regions rather than artifacts due to the Airy diffraction rings or spikes. We also include three additional FUV bright regions without any nearby 24 μm peaks associated (regions 11,12 and 32). Finally, a total of 34 nearly non-overlapping circular apertures of 9″ (∼ 800 pc) in diameter (Figure 1) were selected. The large aperture size is mainly dictated by the PSF of 24 μm and the rather extended emission features for most regions.

Our aperture size for photometry is, in any sense, significantly larger than a typical H II region (Knapen 1998; Oev et al. 2003), and even larger than a typical central star-forming region of a starburst galaxy. However, as is already found by Zhang et al. (2001), the spatial distribution of the young star clusters tends to be correlated up to physical scale of ∼ Kpc. Bastian et al. (2006) have studied several star cluster complexes with sizes up to several hundred parsecs in the Antennae, they found that the young cluster complexes often share the same general velocity distribution with associated giant molecular clouds (GMCs), and even some complexes themselves are clustered. Our star-forming regions are usually spatially resolved into one or few such bright star cluster complexes dominated by few bright star clusters on the high-resolution optical/NIR imaging (e.g. Whitmore et al. 1999; Mengel et al. 2005). Therefore, most of our regions should be supposed to be complexes of star clusters over extended background stellar populations. We note that some regions show slight, yet not systematic, displacement (∼ 1 – 2″) between the 24 μm and the associated FUV peaks. The displacement may indicate that IR and UV emission are dominated by different clusters within these regions.

Although the measured FWHMs of the GALEX PSFs are close to that of the PSFs in MIPS 24 μm image, we apply point source aperture corrections to FUV (1.206), NUV (1.269) and other bands (1.982). Aperture corrections are determined from photometry with increasing aperture radii of isolated field stars in the image fields. All the fluxes have been corrected for foreground Galactic extinction using a value of E(B-V) = 0.046 (Schlegel, Finkbeiner & Davis 1998) and Cardelli, Clayton & Mathis (1989) extinction law with R_V=3.1. The uncertainties assigned to the photometric values are a quadratic sum of three contributions: variance of the local background, photometric calibration uncertainty (5% for FUV and WFPC2, 3% for NUV, 10% for IRAC, and 4% for 24 μm), and poisson statistics noise.

3 BROADBAND SEDS

Figure 2 shows the broadband SEDs for some representative regions across the Antennae galaxies as compared to that of entire Arp 220 and the local H II galaxy NGC 2798 (Kimmey et al. 1993). There are some very remarkable differences of the SEDs between different regions across the whole system of the Antennae galaxies.

In the IR dust emission bands, 24 μm very small

Figure 1. Left: Circular apertures of 9″ in diameter were selected mainly as 24 μm peaks and superposed on color-composite images generated from MIPS 24 μm (red), HST Hα (green), and GALEX FUV(blue) maps of the Antennae. The HST Hα map has been degraded to match the resolution of MIPS 24 μm. The cross signs mark the nuclear centers of the two colliding galaxies. Pixel scales are 1.5″. Right: Color composite image generated from the IRAC 8 μm (red), HST F814W (green) and Hα (blue) maps at their original resolutions (re-sampled to 1.5″ pixel scales). The pixel scales of the two figures are 1.5″. The original resolution of IRAC 8 μm is ∼ 2″. The mosaiicked HST images originally have ∼ 0.1″ pixels (undersampled). At the adopted distance, 1″ corresponds to ∼ 93 pc.
grains (VSGs) and 8 µm PAH emission (for high-metallicity regions) all show very good correlation with extinction-corrected hydrogen recombination emission from starburst regions of normal galaxies to luminous IR galaxies (LIRGs) and ULIRGs (Alonso-Herrero et al. 2004; Calzetti et al. 2007). Nevertheless, the 8 µm PAH emission is progressively depressed relative to 24 µm with increasing star formation intensities (e.g. Calzetti et al. 2003; Smith et al. 2007; Draine & Li 2007; Thilker et al. 2007). Hence, the 24 µm/8 µm ratio would give a rough manifestation of different strengths of current star formation activities across the whole system.

Obviously, the overlap regions (3 - 9) generally have higher 24 µm/8 µm ratios than other regions in the Antennae, meaning that the overlap regions are the most intense current star-forming sites. Spitzer IRS spectrum (Brandl et al. 2009) also show that the overlap regions have overall the weakest relative strength (normalized to 15 µm continuum flux) of PAH features among all these star-forming regions. High-resolution Optical and NIR observations (Whitmore et al. 1999; Mengel et al. 2005) suggest that the overlap regions host most of the youngest clusters. Region 4, which hosts the well-known MIR “hotspot” (Mirabel et al. 1998) of the overlap regions, has the highest 24 µm/8 µm ratios, even comparable with that of Arp 220. High-quality MIR spectrum (Brandl et al. 2009) obtained from Spitzer IRS more clearly show that region 4 is characterized by very hot dust emission and is among the regions with the strongest strength of the radiation field. The intrinsically brightest star cluster (WS95-80, Whitmore & Schweizer 1993) coincides with region 4.

The regions (16 - 22) in the northern galaxy NGC 4038 have the lowest 24 µm/8 µm ratios and reddest UB colors as compared with other regions, which is consistent with the fact that large number of rather old (100 Myr ~ 500 Myr) star clusters are found there (Whitmore et al. 1999; Mengel et al. 2005).

In the UV wavebands, on the contrary, the Western-loop regions (22-32) have the strongest UV emissions, largest UV excesses, and relatively strong 8 µm (PAH) emissions, yet low 24 µm/8 µm ratios. These are in contrast with those in the overlap regions and indicate their relatively late star formation stage, which is also evidenced by the large Hα bubbles found there (Whitmore et al. 1999).

Brandl et al. (2002) also presents the IRS spectra of the UV brightest region 26, which has significantly weaker strength of the radiation field, yet stronger PAHs emission features, than do the overlap regions, in agreement with our broadband analysis.

The circumnuclear star-forming region of NGC 4038, namely region 33, has 24 µm/8 µm ratio close to that of the overlap regions, suggesting its intense current star formation activity. The prominent, yet redder, UV emission reveals that this region may also hold large post-starburst (> 10 Myr) stellar populations. For the two nuclei regions, NGC 4039 has both weaker 8 µm PAH emission and 24 µm dust emission indicating its lower star formation activity, whereas NGC 4038 has almost the same broadband SEDs as that of the local H II galaxy NGC 2798 in the plotted wavelength range. Thus far there is no strong evidence for the presence of AGN activity in the two nuclei. The IRS spectrum (Brandl et al. 2009) suggest that, both nuclei regions have significantly weaker strength of the radiation field than the overlap regions. In comparison with the southern nucleus region, the northern nucleus region has flatter MIR continuum, stronger PAHs fluxes, yet smaller PAHs equivalent widths. These are consistent with our broadband analysis, i.e. both nuclei regions have weak current star formation strength compared to the overlap starburst regions, and the southern nucleus region has even weaker current star formation strength than does the northern nucleus. The stronger high excitation lines in the southern nucleus region (Brandl et al. 2009) should be attributed to supernovae shocks, which are also strongly evidenced by its very steep radio spectrum (Neff & Ulvestad 2000). We point out that our apertures covering the two nuclei (regions 2, 34) are so large that the surrounding star-forming regions are also included.

When we examine the SEDs variations across the overlap regions, we see an interesting phenomenon. From the central regions, i.e. regions 6 and 7, to both the northwestern (e.g. regions 8, 9) and southeastern (e.g. regions 4) regions, the UV/optical emission gradually become redder and weaker, accompanying with comparable amount of energy fraction re-emitted as IR dust emission. In the following sections, we show that the obvious trends of the SEDs variations across the overlap regions may reflect the star formation modes in the overlap regions.

4 STELLAR POPULATION ANALYSIS

4.1 Methodology

The availability of Hα and MIPS 24 µm, which traces the star formation (unobscured and obscured) on timescales of ~ 10 Myr, FUV and NUV (tracing star formation on timescales of ~ 100 Myr), and the U(F336W) and B(F439W), whose combination in U/B ratio is sensitive (straddles the 4000 Å break) to the fraction of populations younger than a few hundred Myr relative to the old populations, makes it reasonable to roughly probe the star formation histories across the whole merging disks of the Antennae. With χ² minimization technique, we fit the broadband SEDs (FUV-Ks) plus the narrowband Hα photometry for the above selected star-forming regions with superpositions of three single stellar populations (SSPs), namely young (< 10 Myr), intermediate (10 Myr-300 Myr) and old (> 300 Myr) populations. In our fitting, we account for the different extinctions experienced by different populations.

For population synthesis models, we use the new version Starburst99 (Vazquez & Leitherer 2003) SSP models with the Padova 2000 stellar evolution tracks, which include the full AGB evolution. We adopt the multi-power law Kroupa initial mass function (Kroupa 2002). Adoption of the bottom-heavy Salpeter IMF would not change our main conclusions in this paper. Using the metallicity sensitive Mg I line at 8806.8 Å, (Mengel et al. 2002) found a handful of star clusters in Arp 244 with solar metallicity, which is consistent with recent metallicity estimation (Bastian et al. 2004) from more absorption and emission lines in the Antennae. Thus, we fix solar metallicity for all the SSPs models. Since we have narrow-band Hα imagery data, and the regions we studied are all actively star-forming regions, we include gaseous emission into the SSP
models. Besides the nebular continuum emission and several hydrogen emission lines provided by Starburst99, we also account for other strong hydrogen emission lines (i.e. Balmer, Paschen, Brackett and Pfund lines) assuming case B recombination and strong non-hydrogen element emission lines using the line ratios of typical Galactic H II regions compiled by Anders & Frize-v. Alvensleben (2003).

For dust extinction, we use the two-phase dust attenuation recipes developed by Charlot & Fall (2000). The effective absorption curve is proportional to $\lambda^{-0.7}$. One adjustable parameter $\mu$ defines the ratio of the total effective extinction experienced by intermediate/old ($>10$ Myr) to young ($<10$ Myr) populations.

It is becoming well known, from the works of the SINGS team, that the combination of H$\alpha$ and 24 $\mu$m accounts for both the unobscured and obscured current star formation for star-forming regions in galaxies (Calzetti et al. 2007). We adopt the relationship between extinction-corrected H$\alpha$, observed H$\alpha$ and 24 $\mu$m calibrated for the H II regions in the 33 SINGS galaxies (equation 5 in Calzetti et al. (2007)) to obtain the H$\alpha$ extinction, and then use the Charlot & Fall (2000) extinction curve to derive the approximate $A_V$ of the young stellar populations from the following equation

$$A_V = 2.825 \log \left[ 1 + 0.03 \frac{L_{24\mu m}}{L_{H\alpha}} \right]$$

(1)

where $L_{24\mu m}$ is the dust-only 24 $\mu$m monochromatic luminosity and $L_{H\alpha}$ is the observed H$\alpha$ luminosity.

Therefore, we first restrict the variations of the three SSPs to their corresponding age ranges mentioned above in order to model the SEDs of various star-forming regions across the merging disks in the Antennae galaxies. Then
we try to find the best-fit composite models with the $\chi^2$ minimization technique

$$
\chi^2 = \sum_{i=UV}^{K} \left( \frac{F_{obs,i} - a F_{mod,i}}{\sigma(F_{obs,i})} \right)^2
$$

by minimizing Equation 2. In this way, we obtain the four best-fit parameters, namely, the mass of the old ($M_o$), intermediate ($M_i$) and young ($M_y$) populations, the extinction ratio ($\mu$) of intermediate/old to young populations. It should be stressed here that we first fix the extinction $A_V$ with Equation 1 prior to SED modeling, which affects mostly the young stellar populations. This makes our stellar population analysis presented in this paper much less affected by the degeneracy between stellar population and extinction.

4.2 Results of SED-fitting

4.2.1 Best-fit Parameters

Our main fitting results are summarized in Table 1. One should keep in mind that, we are actually comparing relatively clustered younger stellar populations with relatively extended older populations. Hence, the absolute values for the mass ratios between different populations should be sensitive to the size of photometric apertures and the average density of the underlying stellar populations. On that account we mainly focus on the relative changes of the mass ratios between different populations across the system.

We notice that the SED-fitting quality for some overlap regions (i.e. regions 8, 9) is not as good as for most other regions (Figure 2). The possible reason can be either the significant starlight contamination by nearby bright regions or the very faint nature (low S/N ratio) of these two regions at short wavebands. To check the significance of the starlight contamination by nearby bright regions, we also present the broadband SEDs for the four optically faint regions in the overlap region in Figure 3. It can be seen that the contamination by nearby bright regions does not change the overall SEDs shape for these regions. In fact, when we fit the SEDs (excluding the FUV/NUV data) extracted from the images at their original resolutions for these regions, our main conclusions for the overlap regions do not change. Table 2 lists the fitting results for the overlap regions using SEDs extracted from the images at their original resolutions. According to our best-fitting results for these regions, the best-fit ages of intermediate populations $\lesssim 100$ Myr, and the best-fitting ages of old stellar population $\gtrsim 3$ Gyr.

For the mass ratios of intermediate to old populations $M_i/M_o$, the overlap regions have overall smaller values compared to other regions, suggesting the overlap star-forming regions are very young. Northern edge of the overlap regions, i.e. region 9, for example, has the lowest $M_i/M_o$. Whereas the western-loop regions of NGC 4038 have overall the largest $M_i/M_o$ across the whole system, and they are the brightest regions in UV. The western-loop regions host most of the intermediate populations. The ratios of most other regions across the whole system fall in between the overlap and western-loop regions.

For the mass ratios of young to old populations $M_y/M_o$, the overlap regions and some western-loop regions have $M_y/M_o$ larger than all the other regions. The similar contrast could also been seen from the age-averaged mass fraction ratios of young to old populations ($\frac{M_y}{M_o}$). The overlap and western-loop regions host most of the young populations, and they are the most intense current star-forming sites across the whole system.

For the mass ratios of young to intermediate populations $M_y/M_i$, the overlap regions hold the largest values, while the northern regions have overall small $M_y/M_i$, conforming with their weak current star formation activities. We also point out here one interesting finding. That is, across the overlap regions, the northwestern edge, namely region 9, and the southeastern edge, region 4, have the $M_y/M_i$ ratios significantly larger than the central regions, e.g. region 6. We note that the trend still exist after we normalize the mass fraction ratios with their corresponding best-fit ages ($\frac{M_y}{M_o}$).

In the last column of Table 1 we also list the corresponding total starlight absorbed by dust which should be equal to the total infrared (TIR) dust emission. Calzetti et al. (2003) exploited a relationship between $24\mu m$/TIR and $8/24\mu m$ for the star-forming regions in NGC 5194. Considering the similar global properties between the Antennae and NGC 5194, such as similar PAH abundances (the PAH index $\sim 4.5$ according to Draine & Li (2007) dust emission models), comparable TIR (Sanders et al. 2003) and total molecular gas surface density (Wilson et al. 2003), we compare the total starlight absorption from our models with the TIR estimated from dust-only $8\mu m$ and $24\mu m$ using the relation (equation 1 in Calzetti et al. 2003) exploited for the star-forming regions of NGC 5194. The comparison is shown in Figure 4. Obviously, almost all our selected star-forming regions in Arp 244 generally follow the same relation derived in the star-forming regions of NGC 5194. Considering the general consistency, in the following sections, we take the total starlight absorption from our SED-fitting models as the best estimate of TIR for our selected star-forming regions.

4.2.2 Star-Forming Regions of Arp 244 on the IRX-UV Plane

Kong et al. (2004) found that, while the dust extinction is the main factor driving the strong correlation between $L_{TIR}/L_{FUV}$ (hereafter IRX) and UV spectral slope, it is the star formation history that affects the degree of deviation of a star-forming galaxy from the locus of starbursts in the IRX-UV color indices’ plane. It is surely meaningful to plot these indices for the star-forming regions of the Antennae on the IRX-UV color plane. Figure 5 shows the ratio of $L_{TIR}/L_{FUV}$, where TIR is set to be equal to the total starlight absorption obtained from our models, as a function of $\beta_{GLX}$ ($\beta_{GLX} = \log \frac{F_{GLX}}{F_{FUV}} - \log \frac{F_{NUV}}{F_{FUV}}$, see Kong et al. 2004). The solid line represents the tight correlation for starburst galaxies (Kong et al. 2004). Obviously, except the overlap regions, almost all the star-forming regions in Arp 244 lie below the locus followed by starbursts. The three regions that lie above the starburst locus are region 4, 5 and 9. Hence, it can be stated here that except for some localized starburst sites, mainly in the overlap regions, most regions across the whole system are forming stars at a level weaker.
### Table 1. SED-fitting Results.

| Reg. | $\chi^2$ | $\mu$ | $M_y/M_o$ | $M_i/M_y$ | $M_i/M_o$ | $M_y/\text{Age}_{y}$ | $M_i/\text{Age}_{i}$ | $M_y/\text{Age}_{o}$ | log[Total Abs.](erg/s) |
|------|----------|-------|-----------|-----------|-----------|-----------------|-----------------|-----------------|------------------|
| NGC4039 Arms | | | | | | | | | |
| 1 | 1.1 | 0.1 | 0.003 | 7.0e-4 | 0.23 | 2.6 | 0.5 | 41.71 |
| Southern Nucleus | | | | | | | | | |
| 2 | 2.2 | 0.9 | 0.03 | 6.0e-4 | 0.02 | 3.8 | 1.7 | 42.72 |
| Overlap Regions | | | | | | | | | |
| 3 | 2.5 | 0.6 | 0.03 | 0.003 | 0.1 | 6.3 | 20.2 | 43.09 |
| 4 | 2.7 | 0.3 | 0.01 | 0.007 | 0.7 | 10.4 | 11.3 | 43.21 |
| 5 | 4.3 | 0.4 | 0.002 | 0.001 | 0.5 | 7.5 | 12.6 | 42.67 |
| 6 | 2.3 | 0.8 | 0.008 | 0.002 | 0.2 | 3.7 | 29.0 | 42.82 |
| 7 | 4.5 | 1.0 | 0.007 | 0.002 | 0.3 | 8.0 | 9.6 | 42.53 |
| 8 | 4.2 | 1.0 | 0.004 | 7.0e-4 | 0.2 | 11.1 | 6.1 | 42.61 |
| 9 | 5.9 | 0.8 | 0.015 | 1.0e-4 | 0.03 | 1.5 | 5.3 | 42.55 |
| Eastern Regions | | | | | | | | | |
| 10 | 3.0 | 0.9 | 0.01 | 5.0e-4 | 0.03 | 1.5 | 5.3 | 42.55 |
| 11 | 1.8 | 1.0 | 0.05 | 5.0e-4 | 0.01 | 2.1 | 2.1 | 42.46 |
| 12 | 1.9 | 0.9 | 0.05 | 4.0e-4 | 0.008 | 0.4 | 5.0 | 42.55 |
| 13 | 2.8 | 1.0 | 0.01 | 7.0e-4 | 0.07 | 1.3 | 3.4 | 42.60 |
| 14 | 2.1 | 0.3 | 0.01 | 6.0e-4 | 0.06 | 2.0 | 8.7 | 42.28 |
| 15 | 0.9 | 0.5 | 0.04 | 5.0e-4 | 0.01 | 1.3 | 4.3 | 42.36 |
| Northern Regions | | | | | | | | | |
| 16 | 1.3 | 0.1 | 0.07 | 6.0e-4 | 0.008 | 1.5 | 1.7 | 41.57 |
| 17 | 1.5 | 0.2 | 0.1 | 6.0e-4 | 0.005 | 1.1 | 1.7 | 41.82 |
| 18 | 1.1 | 0.2 | 0.04 | 3.0e-4 | 0.007 | 0.7 | 4.3 | 41.91 |
| 19 | 1.0 | 0.3 | 0.05 | 3.0e-4 | 0.006 | 0.6 | 3.7 | 41.89 |
| 20 | 1.1 | 0.2 | 0.07 | 4.0e-4 | 0.006 | 0.6 | 3.4 | 41.62 |
| 21 | 1.2 | 0.1 | 0.04 | 4.0e-4 | 0.009 | 0.9 | 5.8 | 41.78 |
| 22 | 2.2 | 0.1 | 0.06 | 0.001 | 0.02 | 1.7 | 2.8 | 41.92 |
| Western-Loop Regions | | | | | | | | | |
| 23 | 0.5 | 0.5 | 0.03 | 6.0e-4 | 0.02 | 0.3 | 4.4 | 42.42 |
| 24 | 2.3 | 0.7 | 0.09 | 4.0e-4 | 0.004 | 0.7 | 2.9 | 42.09 |
| 25 | 3.1 | 0.8 | 0.03 | 8.0e-4 | 0.02 | 0.8 | 11.6 | 42.46 |
| 26 | 1.9 | 0.7 | 0.2 | 0.007 | 0.04 | 0.5 | 50.0 | 42.72 |
| 27 | 3.1 | 1.0 | 0.2 | 0.006 | 0.03 | 0.4 | 29.6 | 42.72 |
| 28 | 3.8 | 1.0 | 0.2 | 0.002 | 0.01 | 1.3 | 17.4 | 42.30 |
| 29 | 3.1 | 1.0 | 0.2 | 0.003 | 0.02 | 1.8 | 3.0 | 42.26 |
| 30 | 3.0 | 1.0 | 0.1 | 0.002 | 0.02 | 0.6 | 3.2 | 42.43 |
| 31 | 2.5 | 0.7 | 0.3 | 7.0e-4 | 0.02 | 1.2 | 7.4 | 42.50 |
| 32 | 2.6 | 0.1 | 0.02 | 0.002 | 0.1 | 8.0 | 1.5 | 42.05 |
| Circumnuclear Regions of NGC4038 | | | | | | | | | |
| 33 | 1.1 | 0.8 | 0.03 | 4.0e-4 | 0.01 | 0.3 | 1.3 | 42.90 |
| Northern Nucleus | | | | | | | | | |
| 34 | 1.4 | 0.6 | 0.01 | 7.0e-4 | 0.05 | 1.5 | 1.4 | 43.03 |

$\chi^2$ is the reduced minimum $\chi^2$ value. $\mu$ is the extinction ratio of intermediate/old to young populations. $M_y$, $M_i$ and $M_o$ represent the mass of young, intermediate and old populations respectively. $M_y/\text{Age}_{y}$, $M_i/\text{Age}_{i}$ and $M_y/\text{Age}_{o}$ represent the corresponding age-averaged mass fraction ratios. The total starlight absorption obtained from the models is listed in the last column.

### Table 2. Fitting Results for the SEDs (without FUV/NUV) extracted from the images at their original resolutions. Only results for some of the overlap regions which may have significant mutual light contamination are listed.

| Reg. | $\chi^2$ | $\mu$ | $M_y/M_o$ | $M_i/M_y$ | $M_i/M_o$ | $M_y/\text{Age}_{y}$ | $M_i/\text{Age}_{i}$ | $M_y/\text{Age}_{o}$ | log[Total Abs.](erg/s) |
|------|----------|-------|-----------|-----------|-----------|-----------------|-----------------|-----------------|------------------|
| Overlap Regions | | | | | | | | | | |
| 3 | 1.0 | 0.5 | 0.04 | 0.01 | 0.3 | 5.0 | 40.0 | 42.97 |
| 4 | 0.3 | 0.3 | 0.01 | 0.05 | 4.5 | 9.4 | 100.1 | 43.50 |
| 5 | 0.7 | 0.8 | 0.004 | 0.005 | 1.3 | 4.7 | 13.5 | 43.11 |
| 6 | 1.9 | 1.0 | 0.05 | 0.01 | 0.2 | 1.5 | 73.0 | 42.94 |
| 7 | 1.8 | 0.3 | 0.02 | 0.004 | 0.2 | 2.9 | 42.5 | 42.54 |
| 8 | 0.9 | 1.0 | 0.04 | 0.002 | 0.05 | 0.6 | 8.8 | 42.82 |
| 9 | 1.0 | 0.7 | 0.002 | 0.001 | 0.5 | 5.0 | 4.2 | 42.52 |
than that of the starbursts. This is also consistent with our further analysis on star formation histories.

Figure 4 plots the ratios of $L(H\alpha_{\text{corr}})/L(Ks)$ vs. $L_B(U)/L_B(B)$. Star-forming regions in NGC 5194 selected (mainly as 24 $\mu$m peaks) by Calzetti et al. (2005) are shown as small pluses. Also plotted is the archetypical starburst galaxy NGC 7714 as a whole (large cross). The modest total star formation rate ($\sim 3.4$ M$_{\odot}$yr$^{-1}$) and star formation intensity ($\sim 0.015$ $M_{\odot}$yr$^{-1}$Kpc$^{-2}$) of NGC 5194 place it among the quiescently star-forming galaxies, although it hosts a LINER-type nucleus. Calzetti et al. (2005) found that the star-forming regions in NGC 5194 have properties quite similar to that of the normal star-forming galaxies, rather than that of starbursts. Assuming $L_B(U)/L_B(B)$ and $L(H\alpha_{\text{corr}})/L(Ks)$ roughly represent the ratios of recent-to-past and current-to-past star formation strengths, respectively, Figure 4 reveals similar results as that of the IRX-UV diagram. Namely, almost all the star forming regions of Arp 244 have current star formation strength comparable with star-forming regions in quiescently star-forming galaxies (low $L(H\alpha_{\text{corr}})/L(Ks)$), except for some of the overlap and western-loop regions.

### 4.2.3 Emission Excess at IRAC 3.6 $\mu$m and 4.5 $\mu$m

Since we have done relatively sophisticated SED-fitting for these star-forming regions, we could estimate the hot dust emission at IRAC 3.6 $\mu$m and 4.5 $\mu$m which are often assumed to be dominated by stellar photospheric emission in literatures. With the average of 3.6 $\mu$m and 4.5 $\mu$m fluxes as the underlying stellar continuum level, Wang et al. (2004) concluded that most of the emission (>90%) in these two bands comes from direct stellar contribution for the whole system. From our stellar SED-fitting, we could easily see (Figures 2 and 3) the prominent emission excess at 3.6 $\mu$m ($\sim 10\% - 65\%$) and 4.5 $\mu$m ($\sim 10\% - 80\%$) for most of these star-forming regions relative to the stellar (plus nebular continuum) emission, especially for the overlap regions. The significant emission excess at 3.6 $\mu$m and 4.5 $\mu$m brings out the caution needed in using them as representation for the underlying stellar mass, particularly when studying the active star-forming regions. Since we have largely accounted for hydrogen/helium recombination emission in our SED-fitting, according to the existing observations of spectra in these two bands of compact H$\text{\textsc{ii}}$ regions (e.g. Martin-Hernandez et al. 2004; Peeters et al. 2002), the other possible main mechanisms of the emission excess could be vibrationally excited molecular hydrogen emission, atomic fine-structure lines, or very small hot dust (e.g. 3.3 $\mu$m PAH feature) emission.

For region 4, the MIR “hotspot”, the excess emission components contribute $\geq 65\%$ and $80\%$ of the total emission at 3.6 $\mu$m and 4.5 $\mu$m respectively. As is already pointed out by Wang et al. (2004), the extremely high obscuration of region 4 must be responsible for the large excess to some extent. The high-quality MIR spectrum of this region obtained from IRS on board Spitzer is characterized by prominent PAHs and very hot VSGs emission (Brandl et al. 2009). Given the prominent PAH feature emission of region 4, the exceptionally low excess emission flux ratio of 3.6 $\mu$m/4.5 $\mu$m ($\sim 0.9$) can not be accounted for by the pure dust emission models of Draine & Li (2007). Furthermore, the K-band spectra (Gilbert et al. 2000) in the obser-

7 Considering the hot dust emission contribution to Ks band, our estimation should be lower limits.
vations of the compact star clusters coincident with the MIR “hotspots” are characterized by prominent nebular and fluorescent H$_2$ emission with slightly rising continuum toward the red (due to hot dust emission). The fact that region 4 has very flat radio spectrum (Neff & Ulvestad 2000) and prominent PAH feature emission excludes the shock origin of the possible molecular/atomic emission. Thus, the fine-structure lines from heavy elements, the molecular lines from FUV fluorescence in dense photodissociation regions (PDRs) and hot dust (including PAHs) emission may all have significant contribution to the emission excess at IRAC 3.6 µm and 4.5 µm.

Interestingly, the total 4.5 µm flux of region 4 is even ∼20% higher than that of the southern nucleus and nearly equal to that of northern nucleus. In short, the excess emission (either from hot dust or molecule/ionized atoms) at IRAC 4.5 µm bands have nonnegligible (>18%) contribution to the total flux for the whole system.

8 This is obtained by the sum of flux of excess emission for all the star-forming regions selected in this work divided by the total flux for the whole system. So here our estimation is a lower limit for the whole system.

5 DISCUSSION

5.1 Star Formation Histories Across the Whole System

Since we have the mass ratios between the three stellar populations for these star-forming regions, using the best-fit ages of the three populations for each region, we could easily derive the ratios between the age-averaged star formation rate (SFR) for the three (i.e. current, recent and past) star formation epochs related to our three populations (Table 1 and 2). We find that, except for some of the overlap regions and the western-loop regions of NGC 4038, which have the ratios of current-to-past age-averaged SFR (defined approximately as $\frac{M_\text{A}}{A_{\text{age}}}$ for most of the other regions have the ratios $\gtrsim 1$. Specifically, the regions which have the ratios $\gtrsim 10$ are 3, 4, 5, 6, 25, 26, 27, and 28. Hence, it can be said that, some of the overlap and western-loop regions are experiencing bursts of star formation, whereas most of the other regions are forming stars at a moderate level comparable with normal star-forming galaxies. The location of these star-forming regions on the IRX-UV plane (Figure 6) is also consistent with the fact that most of the regions are at a modest star formation intensity. For the ratios of current-to-recent age-averaged SFR (defined as $\frac{M_\text{B}}{A_{\text{age}}}$) (see Table 1), the overlap regions have the ratios $\gtrsim 3$, whereas almost all the other regions have the ratios $\sim 1$. The high $\frac{M_\text{B}}{A_{\text{age}}}$ for the two nuclei may be attributed to their surrounding star-forming regions. Hence, comparing with the overlap regions, the star formation of most regions across the whole system is not only modest (except the western-loop regions) but also continuous during the recent tens of million years (typical best-fit ages of the intermediate stellar populations for these regions). Namely, while both the overlap regions, and the western-loop regions are the most intense current star-forming sites across the whole system, the overlap regions are now experiencing much more violent enhancement of star formation compared to all the other regions.

In fact, the star formation histories for these star-forming regions could also be simply probed through the ratios of $L_\lambda(U)/L_\lambda(B)$ and $L(H\alpha_{\text{corr}})/L(K)_{\text{s}}$, which roughly represent ratios of the recent-to-past star formation strength and the current-to-past star formation strength, respectively. Figure 6 clearly shows that, except for the overlap and western-loop regions, most regions are forming stars at moderate level (low $L(H\alpha_{\text{corr}})/L(K)_{\text{s}}$) comparable with star-forming regions in quiescently star-forming galaxies. And meanwhile these regions host a remarkable fraction of aging stellar populations (small $L_\lambda(U)/L_\lambda(B)$), just like the star-forming regions in NGC 5194. The overall larger ratios $L_\lambda(U)/L_\lambda(B)$ for the overlap, the western-loop and the eastern (to a lesser extent) regions compared with the star-forming regions in quiescently star-forming galaxies indicate that these regions may have just experienced a period of intense starburst in the recent few hundred million years. It is also notable of the much higher ratios of current-to-past star formation strength for some of the overlap and western-loop regions. Wang et al. (2004) also got similar results from the flux ratio of the dust-only IRAC 8 µm and the underlying stellar continuum.
5.2 The 20 cm-to-CO ratio map as star formation efficiency map

Taking advantage of the tight correlation between FIR and radio continuum (Condon 1992, Yun et al. 2001; Bell 2003), which appears to be valid at least on kiloparsec scales in galaxies (Lu et al. 1996, Gao et al. 2001) constructed a star formation efficiency map using the 20 cm-to-CO ratio. Overall, our results of population analysis are consistent with their star formation efficiency map, viz, except some localized starburst sites mainly in the overlap and western-loop regions, most regions across the whole system are forming stars at a quite moderate level comparable with normal star-forming galaxies. This verifies the practice of using radio continuum as an indicator of the star formation and the radio-to-CO ratio maps as representation of star formation efficiency maps in most cases.

Nevertheless, some exceptions do exist, like for some overlap regions of galaxy pairs in high-speed collision. For instance, in the Taffy galaxy a large portion of the synchrotron radio emission may be related to gas collision shocks, rather than supernovae remnants (SNRs, most likely related to recent star formation) shocks (Gao et al. 2003, Zhu et al. 2005). In the overlap regions of the Antennae, Gao et al. (2001) found that the radio-to-CO ratios progressively increase from the southeastern side to the northwestern edge across the overlap regions. However, we note that, the lower radio-to-CO ratio of the southeastern region (4) compared to other overlap regions may be, rather than due to lower star formation efficiency, assigned to other various causes. First, the very flat radio continuum suggests that the 20 cm continuum in region 4, rather than being dominated by synchrotron emission from (maybe) SNRs shocks like other overlap regions, is primarily thermal free-free emission from young, compact H II regions. This means that, in such violent overlap starburst environment, large numbers of supernovae events associated with current star formation epoch have not happened. Second, studies on the local IR/radio correlation within nearby galaxies (e.g. Hughes et al. 2006; Murphy et al. 2006) demonstrate the weak trend of increasing IR/radio ratio with increasing IR luminosity within individual galaxy. Both our TIR estimates (equal to the total starlight absorption) and recent IR estimate based on the 15 μm and 30 μm continuum fluxes (Brandl et al. 2009) suggest that region 4 has the largest IR luminosity across the whole system. Finally, the very hot dust emission, as we have shown above, for the southeastern side (i.e. region 4) implies that most energy there may emit in the MIR regime, which again is different from most of the other regions. Therefore, unlike the usually continuous star formation in a relatively long timespan (≥ 10^8 yr), in the violent galaxies interaction regions, both the strong shocks as a result of cloud-cloud collisions and the strong variations of star formation rate in short timescales (tens of Myr) may all make the 20cm-to-CO ratio fails to be an efficient star formation efficiency indicator.

5.3 Sequential Star Formation Paths in the Overlap Regions

Across the overlap regions (Table 2 and 2), the northwestern edge and the southeastern edge have both higher mass ratios of young to intermediate populations M_\text{y}/M_i (i.e. regions 9 and 4) and higher correspondingly age-averaged SFR ratios M_\text{y}/M_i, than do the central regions (e.g. regions 6). We like to interpret the trends as two sequential star formation paths. One is from the central regions (i.e. regions 6) to the southern edge (e.g. region 4), and the other is from the central to the northwestern edge (e.g. region 9).

To check if there are any trends for the spatial distributions of the star clusters across the overlap regions, we refer to the cluster distribution maps derived by Zhang et al. (2001). We find a slightly proportionally deficit of clusters with ages of tens of Myr for both the northwestern (corresponding to our region 9) and the southern edges compared to the central regions (e.g. region 6). Recently, Mengel et al. (2005) also obtained the spatial distributions for clusters with M_\text{y}-determined and CO-index-determined ages. Interestingly, the distributions also show the relative deficit of intermediate-age (∼10 Myr) clusters for both the northwestern and southern edges, although the sample size and the probed age range are all small compared to that of Zhang et al. (2001). The cluster distributions are in agreement with the sequential star formation paths mentioned above, i.e. both the northwestern and southern regions are just beginning their recent star formation episode.

Jog & Solomon (1992) proposed a physical mechanism to explain the origin of the enhanced star formation occurring in situ in the overlapping regions of a pair of colliding galaxies like the Antennae. In their model, following a collision between galaxies, the H I cloud-cloud collisions from the two galaxies lead to the formation of hot, ionized, high-pressure remnant gas that compresses the outer layers of pre-existing GMCs in the overlapping regions. This makes the GMCs shells become gravitationally unstable, which triggers a starburst in the initially barely stable GMCs. Although generally H I cloud-cloud collisions should be more efficient than that of the GMCs due to the much smaller mean free path of an H I cloud than GMC, the huge concentration of molecular gas in the overlap regions of Arp 244 (Wilson et al. 2003, Gao et al. 2001) may make the GMCs collisions also possible.

Based upon this model, across the overlap regions of Arp 244, the sequential star formation paths we have found can be explained naturally. As the two colliding disks begin to interpenetrate each other, the regions that overlap first, e.g. region 6, may have more of the gravitationally unstable GMCs layers formed first, leading to in situ starburst first there. As the colliding/merging proceeds and the overlapping zone between the two colliding disks bulks up, cloud collisions from the two colliding disks spread to more and more regions, i.e. both the northwest (e.g. to regions 8, 9) and southeast (e.g. to regions 5, 4) of the overlap regions. This leads to progressively lagging starbursts triggered by the radiative shock compressions toward both the northwest and southeast directions of the overlap regions. In short, the identified sequential star formation paths could be the imprints of the interpenetrating process of the two colliding galaxy disks.

Both kinematic analysis (Hibbard et al. 2001) and numerical simulations (Toomre & Toomre 1972, Barnes 1988) suggest that the two galaxies of the Antennae system begun their first close encounter several hundred million years ago, and the two colliding galaxies may have passed their
first close encounter \cite{Mihos, Bothun, & Richstone, 1993}. The first peak of large-scale starburst phase may have just passed in the Antennae \cite{Mihos & Hernquist, 1996}, which can be evidenced by the moderate star formation strengths shown in Figs. 5 & 6, consistent with the star formation efficiency map across the whole system \cite{Gao et al., 2001}. While the moderate, continuous (recent) star formation for most regions is consistent with this scenario, the currently violent enhancement of star formation and the sequential star formation paths for the overlap regions may suggest that now the two colliding galaxies are just launching their second close encounter.

After analyzing H$_2$ ν = 0 – 0 S(3) λ = 9.66 μm line emission obtained by ISOCAM CVF, \cite{Haas, Chini, & Klaas, 2003} found that both the southwestern and northwestern edges of the overlap regions, which are very close to the star-forming region 5 and regions 9, respectively, have exceptionally high L(H$_2$)/L(FIR) ratios that exceed that of all other known galaxies. But the absolute current/recent star formation there (especially the northwestern edge) are very weak, just as we find from population analysis (see Table I and 2). They suggest that the high H$_2$ emission there should be excited by pre-starburst shocks which are caused by cloud–cloud collisions. The low mass fractions of intermediate populations and the very high (age-averaged) mass ratios of young to intermediate populations for the two edges, especially the northwestern edge, indicate there indeed are very young star-forming sites, which are most probably to be triggered by pre-starburst shocks following the second close encounter between the two galaxies. However, recent high-quality observations from Spitzer \cite{Brandl et al., 2009} detected about five times less integrated H$_2$ S(3) line flux than does ISOCAM CVF, and didn’t find the previously claimed strong H$_2$ emission peak in the northern overlap zone. These new observations cast doubt on the pre-starburst shock origin of the H$_2$ emission in the overlap regions.

### 6 SUMMARY

To summarise, taking advantage of the availability of multiwavelength imagery from FUV to 24 μm from GALEX, HST, 2MASS and Spitzer in both high resolution and high sensitivity:

- We compare the broadband SEDs of star-forming regions selected as 24 μm peaks across the whole merging disks of the Antennae galaxies, which provides us a basis to comprehend the complete picture of star formation histories. The large ratios of 24 μm/8 μm for the overlap regions and the blue, strong UV emission for the western-loop regions demonstrate that currently they are the most intense star-forming sites, although the western-loop regions are at a relatively later star formation stage compared to the overlap regions. Most of the other regions, which have redder UB color, weaker IR dust emission and UV emission, across the whole system are forming stars at a quite moderate level during the past ~ 100 Myr.

- We roughly constrain the star formation histories of these active star-forming regions across the whole system, with the degeneracy between stellar population and extinction broken, by including 24 μm dust emission into population analysis. Compared with other regions, the overlap regions are now experiencing much more violent enhancement of star formation, although both the overlap and the western-loop regions are the most intense current star-forming sites across the whole system. Our analysis is in general agreement with the findings of \cite{Gao et al., 2001}, i.e. except for some localized violent starbursts confined mainly in the overlap regions and the western-loop regions of NGC 4038, the bulk of star formation is at a moderate level comparable to that of star-forming regions in quiescently star-forming galaxies.

- We suggest two sequential star formation paths across the famous overlap regions, which may reflect the (second) interpenetrating process of the second passage between the two colliding galaxy disks. We also suggest that the recent star formation of both the northern and southern edges of the overlap zone might be just triggered by pre-starburst shocks.

- We report the nonnegligible (> 18%) excess emission contribution to the total IRAC 4.5 μm for the whole system. The well-known brightest MIR “hotspot” in the overlap regions has total 4.5 μm emission (≥ 80% excess emission) even higher (by ∼ 20%) than that of the nuclear region of NGC 4039 and nearly equals to that of the nuclear region of northern galaxy NGC 4038. The unusually low ratio of 3.6 μm/4.5 μm implies that, in addition to hot dust emission, other emission mechanisms, such as atomic fine-structure lines and vibrationally excited molecular hydrogen lines from dense PDRs, have significant contribution to IRAC 4.5 μm.

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