EXTRA-NUCLEAR STARBURSTS: YOUNG LUMINOUS HINGE CLUMPS IN INTERACTING GALAXIES

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ABSTRACT

Hinge clumps are luminous knots of star formation near the base of tidal features in some interacting galaxies. We use archival Hubble Space Telescope (HST) UV/optical/IR images and Chandra X-ray maps along with Galaxy Evolution Explorer UV, Spitzer IR, and ground-based optical/near-IR images to investigate the star forming properties in a sample of 12 hinge clumps in five interacting galaxies. The most extreme of these hinge clumps have star formation rates of $1−9 M\odot$ yr$^{-1}$, comparable to or larger than the “overlap” region of intense star formation between the two disks of the colliding galaxy system the Antennae. In the HST images, we have found remarkably large and luminous sources at the centers of these hinge clumps. These objects are much larger and more luminous than typical “super star clusters” in interacting galaxies, and are sometimes embedded in a linear ridge of fainter star clusters, consistent with star formation along a narrow caustic. These central sources have FWHM diameters of $\sim70$ pc, compared to $\sim3$ pc in “ordinary” super star clusters. Their absolute $J$ magnitudes range from $M_J \sim −12.2$ to $−16.5$; thus, if they are individual star clusters they would lie near the top of the “super star cluster” luminosity function of star clusters. These sources may not be individual star clusters, but instead may be tightly packed groups of clusters that are blended together in the HST images. Comparison to population synthesis modeling indicates that the hinge clumps contain a range of stellar ages. This is consistent with expectations based on models of galaxy interactions, which suggest that star formation may be prolonged in these regions. In the Chandra images, we have found strong X-ray emission from several of these hinge clumps. In most cases, this emission is well-resolved with Chandra and has a thermal X-ray spectrum, thus it is likely due to hot gas associated with the star formation. The ratio of the extinction-corrected diffuse X-ray luminosity to the mechanical energy rate (the X-ray production efficiency) for the hinge clumps is similar to that in the Antennae galaxies, but higher than those for regions in the normal spiral galaxy NGC 2403. Two of the hinge clumps have point-like X-ray emission much brighter than expected for hot gas; these sources are likely “ultra-luminous X-ray sources” due to accretion disks around black holes. The most extreme of these sources, in Arp 240, has a hard X-ray spectrum and an absorbed X-ray luminosity of $\sim2 \times 10^{41}$ erg s$^{-1}$; this is above the luminosity expected by single high mass X-ray binaries (HMXBs), thus it may be either a collection of HMXBs or an intermediate mass black hole ($\gtrsim 80 M\odot$).

Key words: galaxies: individual (Arp 82, Arp 240, Arp 244, Arp 256, Arp 270, NGC 2207, NGC 2403) – galaxies: interactions – galaxies: starburst

Online-only material: color figures

1. INTRODUCTION

Some of the most luminous extra-nuclear star forming regions known in the local universe lie near the base of tidal structures in interacting galaxies. We have dubbed these regions “hinge clumps” as they lie near the “hinge” of the tail (Hancock et al. 2007). Hinge clumps can have $L_{\text{H}\alpha} > 10^{40}$ erg s$^{-1}$ (Hancock et al. 2007), earning them the label of extra-nuclear starbursts. Their location on the outskirts of galaxy disks means they may be important in enriching the intergalactic medium via winds. Hinge clumps can be more extreme sites of star formation than “tidal dwarf galaxies,” larger but lower density star forming regions found near the ends of tidal features. Hinge clumps may be as common as tidal dwarfs, but are not nearly as well-studied. Hinge clumps bear an intriguing resemblance to the massive star forming regions formed by gravitational instabilities in high redshift disks (e.g., Cowie et al. 1995; Elmegreen et al. 2009; F¨oster Schreiber et al. 2011; Elmegreen & Elmegreen 2014), thus the study of these regions broadens our perspective on high redshift disk evolution.

Our recent analytical models of galaxy interactions (Struck & Smith 2012) have provided insights into why star formation is so intense in these regions. These models sometimes produce intersecting caustics near the base of tidal tails, where a caustic is a narrow pile-up zone produced by orbit crowding. Intersecting gas flows within or between caustics may trigger star formation at these locations, producing hinge clumps. In retrospect, evidence for overlapping waves or compressions in the hinge regions of tidal tails can also be seen in many classical papers that modeled galaxy flybys (e.g., Toomre & Toomre 1972; Elmegreen et al. 1991; Gerber & Lamb 1994). More generally, the higher velocity dispersions in the interstellar gas in interacting galaxies may lead to more massive self-gravitating clouds (Elmegreen et al. 1993; Bournaud et al. 2008; Teyssier et al. 2010), and therefore more efficient star formation and more luminous star forming regions in interacting systems compared to more isolated galaxies.

Numerical and analytical models show that intersecting caustics can be produced in both the inner regions of interacting galaxies as well as in tidal features. Strong prograde encounters
can produce “ocular” structures in disks: eye-shaped ovals formed from intersecting spiral arms (Elmegreen et al. 1991). Luminous knots of star formation are sometimes observed along the “eyelids” and in the “points” of oculars (Elmegreen et al. 2006; Hancock et al. 2007, 2009). In tidal features, models reveal a wide variety of caustic morphologies. A single strong caustic is sometimes produced along the leading edge of tidal features; in other cases, two approximately parallel caustics or two diverging or branching caustics are seen in tidal tails (Elmegreen et al. 1991; Donner et al. 1991; Gerber & Lamb 1994; Struck & Smith 2012). In some tidal features, a diverging caustic branches back toward the main disk, creating a loop-like structure, while in other cases two caustics diverge to produce a double-tail morphology (Struck & Smith 2012). Models also sometimes show a “narrowing” of a tidal feature where two caustics converge (Gerber & Lamb 1994; Struck & Smith 2012). At such intersections between caustics, gas build-up and gravitational collapse is expected to occur, triggering star formation. Converging caustics can also occur in the outer portions of tidal features, potentially producing knots of star formation (Struck & Smith 2012), but most tidal dwarfs may form via gas accumulation and gravitational collapse near the end of a tidal feature (Duc et al. 2004; Bournaud & Duc 2006; Wetzstein et al. 2007).

Continued gas inflow into hinge clumps along caustics may produce sustained star formation in these regions, rather than instantaneous bursts. High spatial resolution imaging is one way to test this hypothesis. At high spatial resolution, knots of star formation in nearby galaxies resolve into multiple young star clusters (Zhang et al. 2001; Larsen 2004; Bastian et al. 2005; Mullan et al. 2011). The most luminous of these young clusters are termed “super star clusters” or “young massive clusters” (e.g., Larsen 2000). For clumps of star formation in the disk of Arp 284W, the average age of the stars in the clump derived from single-burst stellar population synthesis models is older than that found for the observed star clusters in that clump seen in Hubble Telescope images (Peterson et al. 2009). This indicates that more than one generation of stars is present in the region, with the older clusters fading and possibly dissolving with time but still contributing to the total light of the clump.

Regions with sustained star formation may have strong X-ray emission, as very young stars may exist simultaneously with the end products of stellar evolution. Given the high star formation rates (SFRs) in hinge clumps, strong diffuse x-ray emission may be present due to stellar winds, supernovae, and shocks. In spiral and irregular galaxies, the diffuse X-ray luminosity correlates with the SFR (Strickland et al. 2004; Owen & Warwick 2009; Mineo et al. 2012b).

Hinge clumps may also host bright X-ray point sources, as the number of high mass X-ray binaries (HMXBs) is correlated with the SFR in spiral galaxies (Grimm et al. 2003; Gilfanov et al. 2004; Persic et al. 2004; Mineo et al. 2012a). The number of “ultra-luminous” X-ray point sources (ULXs: $L_X > 10^{39}$ erg s$^{-1}$) is also correlated with the SFR in both normal spirals and masses less than $80 M_\odot$ are not expected to produce such high luminosities (Zampieri & Roberts 2009; Belczynski et al. 2010; Swartz et al. 2011; Ohsuga & Mineshige 2011).

In order to better understand star formation in hinge clumps, we have searched the archives of the Hubble Space Telescope (HST) and the Chandra X-ray telescope for available images of a sample of hinge clumps. In Section 2 of this paper, we define our sample of hinge clumps and describe the available data sets. Along with the HST and Chandra data, we also include UV images from the Galaxy Evolution Explorer (GALEX) telescope, infrared images from the Spitzer telescope and the Two Micron All Sky Survey (2MASS), ground-based broadband optical images from the Sloan Digital Sky Survey (SDSS), and published He maps. In Section 3, we describe the photometry. We provide approximate SFRs for the clumps in Section 4. In Section 5, we discuss UV/IR colors for the clumps, and in Section 6, we present the X-ray/UV/IR colors of the clumps. In Section 7 we compare with population synthesis models, and in Section 8 we compare the X-ray luminosities of the clumps with their star formation properties. Conclusions are presented in Section 9. In Appendix A, we describe the individual galaxies in the sample and their morphologies, and in Appendix B, we provide a detailed discussion of the intense star formation regions within the Antennae galaxies.

2. SAMPLE AND DATA

2.1. Sample Selection

To study extra-nuclear star formation in interacting galaxies, we have obtained GALEX UV and Spitzer infrared images of three dozen nearby pre-merger interacting galaxy pairs selected from the Arp (1966) Atlas (the “Spirals, Bridges, and Tails” (SB&T) survey; Smith et al. 2007, 2010). We expanded this search to include other Arp pre-merger pairs with available archival GALEX and Spitzer images (Struck & Smith 2012). We also searched the literature for non-Arp systems with similar morphologies and suitable Spitzer and GALEX images. We identified knots of star formation in these systems by visual inspection of the 8 μm Spitzer images, classifying them as either tidal or disk regions. In a later paper, we will investigate the statistical properties of the full sample of star forming regions. In the current paper, we focus on several systems out of this larger sample that contain prominent hinge clumps, with ample data to allow their detailed study.

We define a hinge clump as a discrete knot of star formation near the base of a tidal tail. To define the “hinge region,” we draw a line from the center of the galaxy through the base of the tail, out to approximately twice the radius of the disk. At right angles to this line in the direction of the spiral of the tail, we draw a second line out from the center of the galaxy, again extending out to approximately twice the radius of the disk. The portion of the tail that lies within this pie slice defines the hinge region. The choice of 90° here is motivated by the analytical models. In tidally perturbed systems, in alternate quadrants of the galaxy material either gains or loses orbital angular momentum. In the former case the material is flung out in tails, which can commonly form sharp outer/inner edge caustics. In the latter case, disk material compresses, making the light falloff much steeper, if not actually a sharp edge. The meeting point of these two “sharpened” edges often appears as a cusp point in tailed galaxies. In the models, most of the strong wave overlaps occur within 90° of the base of the tail.

In the current paper, we focus on five systems hosting hinge clumps with high quality multi-wavelength data available
Table 1  
Hinge Clump Sample

| Clump   | R.A. (J2000) | Decl. (J2000) | Distance* (Mpc) | GALEX? (NUV/FUV) | SDSS? |
|---------|--------------|---------------|-----------------|------------------|-------|
| Arp 82-1 | 08 11 13.9   | +25 13 09.6   | 59.2            | yy               | y     |
| Arp 240-1 | 13 39 52.3   | +30 50 22.8   | 101.7           | yn               | y     |
| Arp 240-2 | 13 39 52.5   | +30 50 17.3   | 101.7           | y                | y     |
| Arp 240-3 | 13 39 53.0   | +30 50 12.9   | 101.7           | y                | y     |
| Arp 240-4 | 13 39 53.6   | +30 50 28.6   | 101.7           | y                | y     |
| Arp 240-5 | 13 39 57.2   | +30 49 46.8   | 101.7           | y                | y     |
| Arp 265-1 | 00 18 49.8   | −10 21 33.8   | 109.6           | y y              | y y   |
| Arp 270-1 | 10 49 46.6   | +32 58 23.9   | 29.0            | yy               | y y   |
| Arp 270-2 | 10 49 47.5   | +32 58 20.3   | 29.0            | yy               | y y   |
| Arp 270-3 | 10 49 48.1   | +32 58 25.2   | 29.0            | yy               | y y   |
| Arp 270-4 | 10 49 51.2   | +32 59 11.7   | 29.0            | y y              | y y   |
| NGC 2207-1| 06 16 15.9   | −21 22 02.6   | 38.0            | y n              | n     |

Note. * Distances from the NASA Extragalactic Database, assuming \( H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1} \), and accounting for peculiar velocities due to the Virgo Cluster, the Great Attractor, and the Shapley Supercluster.

(3.2. Spitzer, GALEX, SDSS, Ha, and 2MASS Data Sets)

Of the five systems in Table 1, all have GALEX NUV images available and two also have GALEX far-UV (FUV) images. All five have both Spitzer near-infrared (3.6 \( \mu \text{m} \) and 4.5 \( \mu \text{m} \)) and mid-infrared (5.8 \( \mu \text{m} \), 8.0 \( \mu \text{m} \), and 24 \( \mu \text{m} \)) images available. But one has ground-based SDSS ugriz images available.

The GALEX FUV band has an effective wavelength of 1516 Å with an FWHM of 269 Å, while the FUV band has an effective wavelength of 2267 Å and FWHM of 616 Å. The GALEX images have 1"5 pixels, and the point spread function has an FWHM of ~5". The Spitzer FWHM spatial resolution is 1"5–2" for the 3.6 \( \mu \text{m} \)–8 \( \mu \text{m} \) bands, and ~6" at 24 \( \mu \text{m} \). The 3.6 \( \mu \text{m} \)–8 \( \mu \text{m} \) images have 0’6 pixel\(^{-1}\), while the 24 \( \mu \text{m} \) images have 2’45 pixel\(^{-1}\). The SDSS pixels are 0’4, and the SDSS FWHM spatial resolution is typically about 1’3. The SDSS u, g, r, i, and z filters have effective wavelengths of 3560 Å, 4680 Å, 6180 Å, 7500 Å, and 8870 Å, respectively. For more details about the Spitzer, GALEX, or SDSS observations, see Smith et al. (2007), Smith et al. (2010), and Elmegreen et al. (2006).

We also obtained copies of published Ha maps for all of the hinge clump systems. These include Ha images of Arp 240 and Arp 256 (Bushouse 1987), Arp 82 (Hancock et al. 2007), Arp 270 (Zaragoza-Cardiel et al. 2013), and NGC 2207 (Elmegreen et al. 2001, 2006). The pixel sizes in these Ha images range from 0’2 to 0’595. When necessary, we registered these images to match those at other wavelengths.

We also utilize near-infrared J, H, and K\(_S\) (1.235 \( \mu \text{m} \), 1.662 \( \mu \text{m} \), and 2.159 \( \mu \text{m} \)) images of these galaxies from the 2MASS survey (Skrutskie et al. 2006). These images have 1’0 pixel\(^{-1}\). Some of the hinge clumps are visible as discrete sources on the 2MASS images. The 2MASS seeing was typically FWHM 2’5–3’4 (Cutri et al. 2006).

2.3. Hubble Space Telescope Data Sets

To study the morphology of these star forming regions at higher resolution, we have searched the HST archives for suitable images. Of our sample, four systems have suitable HST images available that cover the hinge clumps. These galaxies and their HST data sets are listed in Table 2. Together, these four systems host a total of eight hinge clumps.

As can be seen in Table 2, a variety of instruments and filters were used for the HST observations. The data include images obtained with the Wide Field Planetary Camera 2 (WFPC2), the Advanced Camera for Surveys (ACS), the Wide Field Camera 3 (WFC3), and the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS). Bandpass images include the FUV F140LP filter, the near-infrared F160W filter (H band), as well as a range of optical bands. The data that we used were obtained from the Hubble Legacy Archive. The WFPC2 images have a pixel size of 0’1, while the pixel size for the ACS F140LP FUV images is 0’025. The ACS optical and the NICMOS F160W images have 0’05 pixel sizes, while the WFC3 F160W image has 0’09 pixels.

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6 http://ned.ipac.caltech.edu

7 http://hla.stsci.edu/


Table 2  

| Galaxy  | Instrument | Filters | Time (s) | Aperture Correction (s) |
|---------|------------|---------|----------|-------------------------|
| Arp 82  | WFPC2      | F606W   | 1900     | 1.19 ± 0.04             |
| Arp 240 | ACS        | F435W   | 1260     | 1.23 ± 0.15             |
| Arp 240E| WFC3       | F160W   | 2395     | 1.23 ± 0.08             |
| Arp 240W| NICMOS     | F160W   | 2303     | 1.30 ± 0.11             |
| Arp 256 | ACS        | F435W   | 1260     | 1.16 ± 0.02             |
| NGC 2207| WFPC2      | F439W   | 2000     | 1.24 ± 0.05             |

Table 3  

| Galaxy | Data Set | Time (ks) |
|--------|----------|-----------|
| Arp 240| 10,565   | 19.9      |
| Arp 256| 13,823   | 29.5      |
| Arp 270| 2042     | 19.3      |
| NGC 2207| 14,914   | 12.9      |

Table 4  

| Galaxy | Filter | Aperture Correction |
|--------|--------|----------------------|
| Arp 82 | NUV    | 1.19 ± 0.04          |
| Arp 240| NUV    | 1.23 ± 0.08          |
| Arp 256| NUV    | 1.30 ± 0.11          |
| Arp 270| NUV    | 1.16 ± 0.02          |
| NGC 2207| NUV    | 1.24 ± 0.05          |

Note. * Multiplicative Aperture Corrections, for a 5″ radius aperture.

2.4. Chandra Telescope Data

To investigate stellar feedback and evolution in these regions, we searched the Chandra archives for suitable data sets. We found archival Chandra images of 4 interacting systems containing a total of 11 hinge clumps (Table 3).

3. PHOTOMETRY

3.1. Spitzer, GALEX, SDSS, Hα, and 2MASS Photometry

From the Spitzer, GALEX, SDSS, Hα, and 2MASS images, we extracted aperture photometry of the sample hinge clumps using the IRAF phot routine. We used a 5″ radius aperture, which is a compromise between our desire to study detailed regions within the galaxy and the limiting spatial resolution of the GALEX and Spitzer 24 μm images. This aperture corresponds to 0.70 kpc to 2.7 kpc at the distances of these galaxies. We used a sky annulus with the mode sky fitting algorithm, an inner radius of 6″, and an outer radius of 12″.

Aperture corrections were determined for each of the GALEX images by determining the counts within 5″ and 17″ radii for three to eight moderately bright isolated point sources in the field. These values are tabulated in Table 4. For the Spitzer images, we used aperture corrections from the IRAC and MIPS Data Handbooks. No aperture corrections are needed for the SDSS images. We also did not do aperture corrections for the 2MASS data, as these corrections are expected to be small for photometry with 5″ radii (Cutri et al. 2006). They are also expected to be small for the Hα images.

When necessary, the Hα luminosities have been approximately corrected for the nearby [N II] lines in the filter. We assume a 30% calibration uncertainty for the Hα images in addition to the statistical uncertainties. We calculated Hα equivalent widths for the clumps using the SDSS r band flux for continuum, approximately correcting this flux for contamination by Hα. For most of the clumps, this correction is only 7%−10%; it is ∼30% for Arp 82-1, Arp 240-3, and Arp 270-4. For NGC 2207, for the Hα continuum we extrapolated between the HST F555W and F814W bands.

We corrected the SDSS photometry for Galactic reddening as in Schlafly & Finkbeiner (2011), as provided by NED. The GALEX photometry was corrected for Galactic reddening using the Cardelli et al. (1989) attenuation law. The final photometry is given in Tables 5 and 6.

3.2. HST Photometry

The HST morphologies of these hinge clumps are often quite remarkable, with a luminous central source embedded in a row of fainter clusters. These linear structures are quite different from the more clustered and amorphous groupings of star clusters seen in HST images of many other galaxies, for example, in the disk of M51 (Bastian et al. 2005). The morphologies of the individual systems are discussed in more detail in Appendix A.

Using the IRAF phot routine we extracted magnitudes for the central sources in the various HST bands using apertures of 0′′.15 radii, and sky annuli with inner radii of 0′′.15 and outer radii of 0′′.30. When necessary, we adjusted the registration of the images obtained with different filters to match. We applied aperture corrections as in Holtzman et al. (1995), Sirianni et al. (2005), Dieball et al. (2007), the NICMOS Instrument Handbook, and the WFC3 Instrument Handbook. We corrected the HST photometry for Galactic extinction using the same method as for the GALEX and SDSS photometry. The final photometry is given in Table 7.

The absolute $I$ magnitudes of the central sources in the hinge clumps,9 uncorrected for internal extinction, range from $M_I = -12.2$ to −16.5. Young unobscured clusters typically have $V − I$ colors of −0.4 to 0.7 (e.g., Chandar & Rothberg 2010), so most of these sources are more luminous than typical super star clusters in interacting galaxies, defined to have absolute $V$ magnitudes $M_V ≤ −11$ (e.g., Larsen 2000). If these sources are individual star clusters, they would lie near the top of the luminosity function of super star clusters (e.g., Gieles 2010). The most luminous of these objects are comparable in luminosity to the most massive star cluster in the Antennae galaxies, which lies in an intense starburst in the “overlap” region between the two galactic disks. This Antennae cluster has

9 These magnitudes and those given in Appendix A are in the Johnson system, using the approximate conversions given in the WFPC2 Photometry Cookbook.
### Table 5

Large Aperture GALEX/SDSS/Spitzer Magnitudes for Sample Hinge Clumps

| Clump   | FUV (mag) | NUV (mag) | u (mag) | g (mag) | r (mag) | i (mag) | z (mag) | 3.6 μm (mag) | 4.5 μm (mag) | 5.8 μm (mag) | 8.0 μm (mag) | 24 μm (mag) |
|---------|-----------|-----------|---------|---------|---------|---------|---------|--------------|--------------|--------------|--------------|-------------|
| Arp 82-1 | 19.09 ± 0.02 | 18.91 ± 0.02 | 18.31 ± 0.03 | 17.87 ± 0.01 | 17.91 ± 0.03 | 18.26 ± 0.05 | 17.90 ± 0.08 | 17.91 ± 0.08 | 14.71 ± 0.01 | 14.43 ± 0.01 | 12.40 ± 0.01 | 10.47 ± 0.01 | 6.44 ± 0.01 |
| Arp 240-1 | ... | 16.83 ± 0.04 | 16.16 ± 0.01 | 15.48 ± 0.02 | 14.97 ± 0.02 | 14.80 ± 0.02 | 14.67 ± 0.03 | 11.92 ± 0.01 | 11.84 ± 0.01 | 9.93 ± 0.01 | 8.02 ± 0.01 | 4.65 ± 0.02 |
| Arp 240-2 | ... | 16.98 ± 0.05 | 16.56 ± 0.03 | 15.60 ± 0.02 | 15.44 ± 0.03 | 15.22 ± 0.03 | 14.88 ± 0.03 | 11.93 ± 0.01 | 11.83 ± 0.01 | 9.90 ± 0.01 | 7.96 ± 0.01 | 4.35 ± 0.02 |
| Arp 240-3 | ... | 17.61 ± 0.12 | 17.36 ± 0.07 | 16.18 ± 0.04 | 16.44 ± 0.08 | 16.04 ± 0.07 | 15.57 ± 0.07 | 12.41 ± 0.01 | 12.21 ± 0.01 | 10.29 ± 0.01 | 8.32 ± 0.01 | 3.98 ± 0.01 |
| Arp 240-4 | ... | 17.05 ± 0.06 | 16.48 ± 0.02 | 15.74 ± 0.02 | 15.49 ± 0.03 | 15.35 ± 0.04 | 15.08 ± 0.04 | 12.00 ± 0.01 | 11.90 ± 0.01 | 10.08 ± 0.01 | 8.12 ± 0.01 | 5.02 ± 0.01 |
| Arp 240-5 | ... | 18.15 ± 0.06 | 17.11 ± 0.03 | 15.97 ± 0.03 | 15.37 ± 0.03 | 14.93 ± 0.03 | 14.62 ± 0.03 | 11.27 ± 0.01 | 11.08 ± 0.01 | 9.05 ± 0.01 | 7.09 ± 0.01 | 3.39 ± 0.01 |
| Arp 256-1 | 17.65 ± 0.04 | 17.38 ± 0.04 | 17.15 ± 0.02 | 16.46 ± 0.02 | 15.79 ± 0.02 | 15.75 ± 0.02 | 15.77 ± 0.03 | 12.88 ± 0.01 | 12.72 ± 0.01 | 10.84 ± 0.01 | 8.85 ± 0.01 | 5.53 ± 0.01 |
| Arp 270-1 | 18.20 ± 0.04 | 18.33 ± 0.06 | 17.91 ± 0.03 | 17.73 ± 0.02 | 17.58 ± 0.03 | 17.80 ± 0.04 | 17.78 ± 0.08 | 14.71 ± 0.01 | 14.62 ± 0.01 | 12.57 ± 0.01 | 10.89 ± 0.01 | 7.88 ± 0.02 |
| Arp 270-2 | 18.57 ± 0.09 | 18.60 ± 0.11 | 18.40 ± 0.06 | 17.81 ± 0.04 | 17.61 ± 0.04 | 17.78 ± 0.05 | 17.85 ± 0.10 | 14.48 ± 0.02 | 14.32 ± 0.02 | 12.13 ± 0.01 | 10.33 ± 0.01 | 7.33 ± 0.03 |
| Arp 270-3 | 18.18 ± 0.14 | 18.31 ± 0.18 | 17.96 ± 0.06 | 17.58 ± 0.06 | 17.42 ± 0.07 | 17.51 ± 0.08 | 17.73 ± 0.11 | 14.37 ± 0.02 | 14.15 ± 0.02 | 12.04 ± 0.02 | 10.27 ± 0.01 | 7.18 ± 0.03 |
| Arp 270-4 | 17.13 ± 0.09 | 17.11 ± 0.13 | 16.91 ± 0.04 | 16.48 ± 0.06 | 16.57 ± 0.05 | 16.69 ± 0.07 | 16.57 ± 0.09 | 13.12 ± 0.01 | 12.98 ± 0.01 | 10.71 ± 0.01 | 8.92 ± 0.01 | 5.83 ± 0.01 |
| NGC 2207-1 | ... | 17.68 ± 0.07 | ... | ... | ... | ... | ... | 12.31 ± 0.01 | 11.84 ± 0.01 | 9.69 ± 0.01 | 7.79 ± 0.01 | 3.03 ± 0.01 |

**Note.** a Zero magnitude flux densities are 3631 Jy for the GALEX and SDSS bands, and 277.5 Jy, 179.5 Jy, 63.1 Jy, and 7.3 Jy for 3.6 μm, 4.5 μm, 5.8 μm, 8.0 μm, and 24 μm, respectively.
et al. 2010). The Astronomical Journal in low luminosity spirals have many nuclear star clusters, for example, the nuclear star clusters clumps from the of the blending of multiple clusters closely packed together in a central regions of the hinge clumps may be the consequence Thus we conclude that the large sizes we measure for the larger sources similar in size to those seen in the hinge clumps. multiple star clusters would appear blended together, creating that, if the Antennae were at the distance of the hinge clumps, photometry given in Tables 1 and 2. In most cases, we used sky GALEX ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ... ......
superimposed on an extended soft component. The X-ray spectra are generally soft and in most cases appear dominated by a power law spectrum. The point source in clump 4 in Arp 240W has a thermal spectrum, but this is not well-constrained.

( clump 4 in Arp 240W), there is a point-like hard component superimposed on an extended soft component. The X-ray morphologies of the individual sources are discussed further in Appendix A.

We extracted X-ray fluxes for these clumps, and used Cash statistics to analyze their X-ray spectra. No background fluxes were present in the data, so no filtering was needed. The X-ray spectra are generally soft and in most cases appear dominated by thermal emission (Figure 1). In Table 9, we provide the observed 0.3–8 keV flux for the central X-ray source, along with a rough estimate of its size and its coordinates.

Clump 1 in Arp 240W has an X-ray spectrum consistent with a thermal plasma. Clump 2 is also probably a thermal plasma, but has too few counts to strongly constrain the parameters. Although clump 3 in Arp 240W is unresolved with Chandra, its X-ray spectrum is intrinsically soft but appears highly absorbed, consistent with a hot plasma (for example, a compact starburst region with diameter $\lesssim 300$ pc or a disk blackbody), rather than a power law spectrum. The point source in clump 4 in Arp 240W has a very hard spectrum, with 80 counts between 1.2 and 7 keV, and only 2 counts $\lesssim 1.2$ keV, and may be very absorbed (see Figure 1). The spectrum can be fit with a power law with a photon index $\gamma = 2.7 \pm 0.8$. Clump 5, at the base of the southern tail in Arp 240E, is extended with a thermal spectrum. The point source in clump 1 of Arp 270 may also be a highly absorbed thermal spectrum, but this is not well-constrained.

We are not able to provide strong constraints on the absorbing hydrogen column density of any of these sources based on the X-ray spectra. We therefore estimated the absorption using the $L_{24}/L_{60}$ ratios. These corrections and the corrected luminosities are discussed at length in Section 7.3. To match the large-aperture GALEX/SDSS/Spitzer/HST photometry, we also obtained X-ray luminosities within a 5" radius aperture. In most cases, these are less than twice that of the central source.

### 3.4. Photometry of Comparison Systems

To put these hinge clumps into perspective, we compare them to star forming regions in other galaxies. We focus in particular on two comparison systems that have high quality X-ray data available in addition to UV/optical/IR images: the Antennae galaxies and the normal spiral galaxy NGC 2403.

For the Antennae, we use the 4.5 radius (530 pc) Spitzer GALEX, and ground-based H$\alpha$ photometry of 34 positions provided by Zhang et al. (2010). Most of these positions were selected based on peaks in the 24 $\mu$m map, although three were selected based on GALEX UV sources.

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**Table 8**

| Clump     | F140LP | F435W | F439W | F555W | F606W | F814W | F160W |
|-----------|--------|-------|-------|-------|-------|-------|-------|
| Arp 82-1  | ...    | ...   | ...   | ...   | 2.65±0.01 | 1.34±0.01 | ...   |
| Arp 240-1 | 73.86±0.01 | 33.13±0.01 | ...   | ...   | 2.65±0.01 | 1.34±0.01 | ...   |
| Arp 240-2 | 61.92±0.01 | 26.90±0.01 | ...   | ...   | 17.29±0.01 | 20.09±0.07 | ...   |
| Arp 240-3 | 32.12±0.01 | 14.19±0.01 | ...   | ...   | 14.35±0.01 | 14.55±0.06 | ...   |
| Arp 240-4 | 69.16±0.01 | 25.36±0.01 | ...   | ...   | 8.07±0.01  | 5.76±0.06  | ...   |
| Arp 240-5 | 16.06±0.01 | 23.34±0.02 | ...   | ...   | 13.93±0.01 | 6.47±0.11  | ...   |
| Arp 256-1 | 44.42±0.01 | 13.02±0.01 | ...   | ...   | 20.34±0.01 | 12.39±0.01 | ...   |
| NGC 2207-1| ...     | ...   | 13.88±0.03 | 9.30±0.01 | 6.99±0.01  | 10.59±0.02 | ...   |

**Note.** These fluxes are all within a 5" radius. All fluxes are in units of $10^{-16}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$, and have been corrected for Galactic extinction as described in the text.

| Clump     | R.A.$^a$ | Decl.$^a$ | Background-subtracted Counts | Flux$^b$ (erg s$^{-1}$ cm$^{-2}$) | Size$^c$ (') | $L_x$$^d$ (erg s$^{-1}$) (0.3–8 keV) | $L_x$$^e$ (erg s$^{-1}$) (0.3–8 keV) |
|-----------|----------|----------|-------------------------------|---------------------------------|-------------|-----------------|-----------------|
| Arp 240-1 | $13^h 19^m 52^s 28''$ | $+00^\circ 50' 21''$ | 29 | $3.2 \times 10^{-15}$ | $1.5 \times 0.3$ | $1.5 \times 10^{39}$ | $2.2 \times 10^{39}$ |
| Arp 240-2 | $13^h 19^m 52^s 29''$ | $+00^\circ 50' 15''$ | 18 | $3.2 \times 10^{-15}$ | $1.5 \times 1.5$ | $1.8 \times 10^{39}$ | $5.4 \times 10^{39}$ |
| Arp 240-3 | $13^h 19^m 52^s 95''$ | $+00^\circ 50' 12''$ | 17 | $4 \times 10^{-15}$ | $\lesssim 0.75 \times 0.75$ | $3.3 \times 10^{39}$ | $5.0 \times 10^{39}$ |
| Arp 240-4 | $13^h 19^m 53^s 51''$ | $+00^\circ 50' 30''$ | 99 | $39 \times 10^{-15}$ | $\lesssim 0.65 \times 0.65$ | $17.8 \times 10^{39}$ | $21.9 \times 10^{39}$ |
| Arp 256-1 | $00^h 18^m 40''$ | $+49^\circ 46^''$ | 86 | $12.1 \times 10^{-15}$ | $4.8 \times 4.8$ | $14.2 \times 10^{39}$ | $14.2 \times 10^{39}$ |
| Arp 270-1 | $10^h 49^m 46''$ | $+32^\circ 58' 23''$ | 50 | $15 \times 10^{-15}$ | $0.85 \times 0.85$ | $0.4 \times 10^{39}$ | $0.4 \times 10^{39}$ |
| Arp 270-2 | ... | ... | $\lesssim 6$ | $\lesssim 1.2 \times 10^{-15}$ | ... | $\lesssim 0.4 \times 10^{39}$ | $\lesssim 0.4 \times 10^{39}$ |
| Arp 270-3 | ... | ... | $\lesssim 6$ | $\lesssim 1.5 \times 10^{-15}$ | ... | $\lesssim 0.4 \times 10^{39}$ | $\lesssim 0.3 \times 10^{39}$ |
| Arp 270-4 | ... | ... | $\lesssim 6$ | $\lesssim 1.4 \times 10^{-15}$ | ... | $\lesssim 0.3 \times 10^{39}$ | $\lesssim 0.3 \times 10^{39}$ |
| NGC 2207-1 | $16^h 16^m 15^s 55''$ | $-21^\circ 22' 02''$ | 26 | $11 \times 10^{-15}$ | $10 \times 6$ | $2.5 \times 10^{39}$ | $2.5 \times 10^{39}$ |

**Notes.**

$^a$ Coordinates of the central Chandra source.

$^b$ Observed flux from the source in the center of the clump.

$^c$ Approximate total angular extent of X-ray emission from the central source within the clump.

$^d$ X-ray luminosity of the central source within the clump; corrected for internal extinction using estimates made from the $L_{60}/L_{24}$ ratio as described in the text.

$^e$ X-ray luminosity within a 5" radius aperture. Corrected for internal extinction using estimates made from the $L_{60}/L_{24}$ ratio as described in the text.
earlier studies of the Antennae (e.g., Fabbiano et al. 2001, 2004; and an absorbing column $N_H \sim 1.5 \times 10^{22}$ cm$^{-2}$. The small number of counts and the small energy range available for spectral fitting do not allow us to constrain the absorbing column or distinguish between a power law model and a curved model (e.g., a Comptonized disk-blackbody). Right: the X-ray spectrum of the source in Arp 240E. The spectrum is fit with a two-component model, in which the column densities of the two components differ, but the temperatures are the same. The best fit temperature is $kT = 0.30 \pm 0.09$ keV. The dominant component is highly absorbed ($N_H = 1.6 \times 10^{22}$ cm$^{-2}$), while the second is $2 \times 10^{20}$ cm$^{-2}$, near the Galactic value.

(A color version of this figure is available in the online journal.)

To augment this UV/optical/IR photometry, we used archival Chandra data for the Antennae galaxies. We combined six Chandra observations of the Antennae (ObsID 700479/80/81/82/83) taken in the FAINT mode and removed flares with a sigma clipping method ($2.5 \sigma$), giving a total of 329 ks of observations. This Chandra data has been used in numerous earlier studies of the Antennae (e.g., Fabbiano et al. 2001, 2004; Zezas & Fabbiano 2002; Zezas et al. 2002a, 2002b, 2006), with the diffuse X-ray emission in the Antennae previously being studied by Metz et al. (2004) and Brassington et al. (2007). We extracted X-ray fluxes for the 34 Zhang et al. (2010) regions, using 4′.5 (530 pc) radius apertures. In Appendix B, we provide a detailed discussion of the overlap region of the Antennae, including its X-ray spectra, for comparison to the hinge clumps.

We also compare the hinge clumps to star forming regions within the normal spiral galaxy NGC 2403. For the star forming regions in NGC 2403, we used IRAF to extract Spitzer and GALEX photometry from archival data using the same positions and apertures as used by Yukita et al. (2010) to measure the diffuse X-ray emission. These apertures have radii of 7′.3–13′.8, corresponding to 110 pc to 210 pc. For this photometry, we used background annuli with inner and outer radii of 13′.8 and 20′, respectively, and the mode sky fitting algorithm. We repeated this process for narrowband H$\alpha$ and off-H$\alpha$ red continuum images of NGC 2403 from L. van Zee et al. (2014, in preparation).

In Section 5 of this paper, we also compare the UV/optical/IR colors of the hinge clumps with published values for star forming regions within other strongly interacting galaxies as well as regions within the Magellanic Clouds.

4. STAR FORMATION RATES

The H$\alpha$ luminosities for some of the hinge clumps are very high (Table 6). Of our 12 hinge clumps, 9 have observed $L_{H\alpha}>10^{40}$ erg s$^{-1}$ and 6 have $L_{H\alpha}>10^{41}$ erg s$^{-1}$. For comparison, 30 Doradus in the Large Magellanic Cloud has an observed $L_{H\alpha}$ of only $5 \times 10^{39}$ erg s$^{-1}$, and the giant H$\alpha$ region complex NGC 5461 in M101 has an observed $L_{H\alpha} \sim 1.5 \times 10^{40}$ erg s$^{-1}$ (Kennicutt 1984).

To complement the H$\alpha$ luminosities, in Table 10 we provide monochromatic luminosities ($\nu L_{\nu}$) of the hinge clumps in the NUV and 24 μm bands. Six of our 12 hinge clumps have $L_{NUV}$ larger than all 10 of the tidal dwarf galaxies in the SB&T sample (Smith et al. 2010). Seven of the hinge clumps have $L_{24} \geq 6 \times 10^{42}$ erg s$^{-1}$. For context, out of a sample of 26 normal spirals, only four have total 24 μm luminosities in this range (Smith et al. 2007). The entire 24 μm luminosity for the Antennae is $2 \times 10^{43}$ erg s$^{-1}$, and for the starburst galaxy Arp 284 it is $3 \times 10^{43}$ erg s$^{-1}$ (Smith et al. 2007).

In Table 10, we also provide two estimates of the SFRs of the clumps. First, we use the equation SFR ($M_{\odot}$ yr$^{-1}$) = $5.5 \times 10^{-42}$[$L_{H\alpha} + 0.031 L_{24}$] (erg s$^{-1}$), where the 24 μm luminosity $L_{24}$ is defined as $\nu L_{\nu}$. This relationship was found for H$\alpha$ regions in nearby galaxies assuming a Kroupa initial mass function (IMF; Calzetti et al. 2007; Kennicutt et al. 2009). We make a second estimate of the SFR from the NUV luminosity first correcting for extinction using $L_{NUV(corr)} = L_{NUV} + 2.26 L_{24}$ and then using the relation log(SFR) = log($L_{NUV(corr)}$) − 43.17, where $L_{NUV} = \nu L_{\nu}$ (Hao et al. 2011; Kennicutt & Evans 2012). The two methods agree reasonably well (Table 10). There is a large range in the inferred SFR for the hinge clumps in our sample, from fairly low values ($0.02 M_{\odot}$ yr$^{-1}$ for Arp 270-1) to very high values. Seven of the 12 hinge clumps have estimated SFRs greater than $1 M_{\odot}$ yr$^{-1}$, with the highest being Arp 240-5, with a rate of $9 M_{\odot}$ yr$^{-1}$.

For the two methods of estimating SFR, using global fluxes we calculated the total SFR for the parent galaxies of the target hinge clumps and compared with the SFR for the hinge clump itself. The percent of the total SFR from the galaxy due to the hinge clump ranges from 1% in Arp 270-1 and Arp 270-2 to 56% in Arp 240-5 (Table 10).

These estimates of SFR are very approximate, as these formulae were derived assuming constant SFRs over the last ~10–100 Myr (see Kennicutt & Evans 2012), while the clumps...
13.3 Mpc was found by Saviane et al. (2008) based on the apparent tip of the Great Attractor, and the Shapley Supercluster. A smaller distance of 22.3 Mpc based on a type Ia supernova. They suggest that the latter result was questioned by Schweizer et al. (2008), who find 22.3 Mpc compared to those of Hα regions within other galaxies (e.g., Boquien et al. 2007, 2009b, 2011; Kennicutt et al. 2007; Cao & Wu 2007; Beirão et al. 2009; Pancoast et al. 2010) as well as galaxies as a whole (e.g., Kennicutt & Evans 2012).

For comparison to the hinge clumps, we calculated SFRs for the Antennae regions using the two methods described above. In these calculations, we assume a distance of 24.1 Mpc to the Antennae. The most intense star formation in the Antennae is occurring in regions 3 and 4 from the Zhang et al. (2010) study, which lie in the overlap region. For these regions, the implied SFRs exceed these rates (see Table 10). Summing over all of the regions in the Antennae, we find a total SFR for the Antennae of 9–12 M⊙ yr⁻¹ for the two methods.

Although several of these hinge clumps have very high SFRs, their Hα equivalent widths (Table 6) are not particularly high, compared to those of Hα regions within other galaxies (e.g., Cedres et al. 2005; Boquien et al. 2009a; Popping et al. 2010; Sanchez et al. 2012). This suggests that the hinge clumps contain a wide range of stellar ages and possibly a considerable underlying older stellar population. The areas covered by our Hα photometry of individual Hα regions in nearby galaxies, thus we are likely adding light from surrounding older stars to the continuum flux. Other factors that may affect the Hα equivalent width include extinction variations within the clump, metallicity effects, stellar absorption of Hα, and differences in the IMF.

For the hinge clumps, in calculating this distance we assume H₀ = 73 km s⁻¹ Mpc⁻¹ and account for peculiar velocities due to the Virgo Cluster, the Great Attractor, and the Shapley Supercluster. A smaller distance of 13.3 Mpc was found by Saviane et al. (2008) based on the apparent tip of the red giant branch. The latter result was questioned by Schweizer et al. (2008), who find 22.3 Mpc based on a type Ia supernova. They suggest that the 13.3 Mpc estimate was probably due to a mis-identification of the red giant branch. For more information, see Tammann & Reindl (2013).

### Table 10

| Clump          | L_{NUV}^a (erg s⁻¹) | L_{24}^b (erg s⁻¹) | SFRc (M⊙ yr⁻¹) | Percentd | SFRc (M⊙ yr⁻¹) | Percentd |
|----------------|---------------------|--------------------|----------------|-----------|----------------|-----------|
| Arp 82-1       | 5.5 × 10^{41}       | 10.2 × 10^{41}     | 0.29           | 7%        | 0.18           | 5%        |
| Arp 240-1      | 109.9 × 10^{41}     | 155.4 × 10^{41}    | 4.04           | 19%       | 3.06           | 18%       |
| Arp 240-2      | 96.0 × 10^{41}      | 206.5 × 10^{41}    | 4.83           | 22%       | 3.73           | 22%       |
| Arp 240-3      | 53.4 × 10^{41}      | 290.0 × 10^{41}    | 6.11           | 28%       | 4.7            | 28%       |
| Arp 240-4      | 89.8 × 10^{41}      | 110.7 × 10^{41}    | 2.76           | 13%       | 2.25           | 13%       |
| Arp 240-5      | 32.5 × 10^{41}      | 498.3 × 10^{41}    | 9.45           | 56%       | 7.69           | 55%       |
| Arp 256-1      | 76.9 × 10^{41}      | 80.4 × 10^{41}     | 2.01           | 43%       | 1.71           | 40%       |
| Arp 270-1      | 2.2 × 10^{41}       | 0.6 × 10^{41}      | 0.02           | 1%        | 0.02           | 1%        |
| Arp 270-2      | 1.8 × 10^{41}       | 1.1 × 10^{41}      | 0.02           | 1%        | 0.02           | 1%        |
| Arp 270-3      | 2.3 × 10^{41}       | 1.2 × 10^{41}      | 0.04           | 2%        | 0.03           | 1%        |
| Arp 270-4      | 6.9 × 10^{41}       | 4.3 × 10^{41}      | 0.19           | 8%        | 0.11           | 5%        |
| NGC 2207-1     | 7.0 × 10^{41}       | 97.1 × 10^{41}     | 1.74           | 24%       | 1.5            | 22%       |

Notes.

- a Using $L_{NUV} = v L_{\nu}$.
- b Using $L_{24} = v L_{\mu m}$.
- c Calculated using SFR ($M_{\odot} yr^{-1}$) = 5.5 × 10^{-42}(L_{H\alpha} + 0.031 L_{24}) (erg s⁻¹) (Kennicutt et al. 2009).
- d Percent of total SFR from the parent galaxy in the target clump.
- e Calculated using $L_{NUV}(corr) = L_{NUV} + 2.26 L_{24}$ and log(SFR) = log($L_{NUV}(corr) - 43.17$ (Hao et al. 2011).

In Figure 2, we plot the [3.6 μm]–[24 μm] colors of the hinge clumps versus the [8.0 μm]–[24 μm] and NUV–[24 μm] colors. We compare these values with published photometry for star forming regions in several other interacting galaxies. These

5. UV/IR COLORS

In Figure 2, we plot the [3.6 μm]–[24 μm] colors of the hinge clumps versus the [8.0 μm]–[24 μm] and NUV–[24 μm] colors. We compare these values with published photometry for star forming regions in several other interacting galaxies.
include knots of star formation within the disks of the Antennae galaxies (Arp 244; Zhang et al. 2010), additional star formation regions in Arp 82 besides the hinge clump (from Hancock et al. 2007), as well as tidal and disk clumps in the interacting galaxies Arp 107 (Smith et al. 2005; Lapham et al. 2013), Arp 24 (Cao & Wu 2007), and Arp 143 (Beirão et al. 2009), along with Arp 105 and Arp 245 (Boquien et al. 2010). In this figure, we excluded sources that are likely to be foreground/background objects not associated with the galaxies (see Lapham et al. 2013). In the left panel of Figure 2, we also include Spitzer colors for H II regions in the Small and Large Magellanic Clouds (Lawton et al. 2010). In Figure 2, we also compare with star forming regions within the normal spiral galaxy NGC 2403, as discussed in Section 3.4.

As can be seen in Figure 2, there is a range of colors for the hinge clumps, however, on average, the hinge clumps have redder [3.6]–[24] colors (i.e., higher $L_{24}/L_{3.6}$ ratios) than the other clumps. The 3.6 μm emission from galaxies is generally assumed to be dominated by light from the older stellar population/underlying stellar mass (e.g., Helou et al. 2004), while the 24 μm light is emitted from “very small interstellar dust grains,” heated mainly by UV light from massive young stars (e.g., Li & Draine 2001). Thus a red [3.6]–[24] color implies very obscured star formation, a very young burst, and/or a high young/old stellar mass ratio.

The [3.6]–[24] colors of some of the hinge clumps approach that of the “overlap” region in the Antennae galaxies (Figure 2). The overlap region corresponds to regions 3 and 4 in the Zhang et al. (2010) Antennae study, with region 4 being more obscured. In particular, the [3.6]–[24] color of the NGC 2207 region is similar to that of regions 3 and 4, and is much redder than the other hinge clumps. The Arp 82 hinge clump and Arp 240 clump are also quite red in this color. This supports the idea that these are young regions.

Figure 2 shows that the [3.6]–[24] color is correlated with [8.0]–[24] colors, with some of the hinge clumps having very red [8.0]–[24] colors. The [8.0]–[24] color is a function of the ultraviolet interstellar radiation field (ISRF), with a stronger ISRF producing a higher 24 μm flux compared to that at 8 μm (i.e., a redder [8.0]–[24] color; Li & Draine 2001; Peeters et al. 2004; Lebouteiller et al. 2011). The 8 μm Spitzer band contains emission from both very small dust grains and polycyclic aromatic hydrocarbons (PAHs). PAHs can be excited by non-ionizing photons as well as UV, so the 8 μm emission may be powered in part by lower mass stars (Peeters et al. 2004; Calzetti et al. 2007; Lebouteiller et al. 2011). The Small Magellanic Cloud regions have redder [8.0]–[24] colors for a given [3.6]–[24] color, likely caused by fewer PAHs in the 8 μm band. Low metallicity dwarfs tend to be deficient in the 8 μm Spitzer band compared to normal spirals (Engelbracht et al. 2005; Rosenberg et al. 2006, 2008; Draine et al. 2007; Wu et al. 2007).

The FUV to infrared ratio has sometimes been used as an indicator of dust reddening (e.g., Boquien et al. 2009a), with redder colors meaning more absorption of the UV by dust. Since some of our hinge clumps do not have FUV images available, we use NUV – [24] as an alternative indicator of extinction. Figure 2 shows that there is a range in extinction for the hinge clumps. In Figure 2, the NUV – [24] color correlates to some extent with [3.6]–[24], but there is considerable scatter. In general, the regions within the Antennae are more obscured than many of the other clumps for the same [3.6]–[24] color, particularly those in the normal spiral NGC 2403. Zhang et al. (2010) region 4, in the overlap region of the Antennae galaxies, is particularly red in NUV – [24].
Interestingly, some of the NGC 2403 regions also lie to the right of the correlation marked by the clumps in the interacting galaxies, in the regime populated by the Magellanic Cloud regions. This may also be a metallicity effect. The red NGC 2403 regions are preferentially found at larger galactic radii. NGC 2403 is a moderate luminosity ($M_B = -18.9$; Moustakas et al. 2010) late-type (Scd) spiral. The NGC 2403 region with the largest $[3.6]–[24]$ color, J073628.6+653349, has a deprojected distance from the nucleus of 6.21 kpc (Garnett et al. 1997). Its oxygen abundance has been determined by the direct electron temperature method to be log(O/H) + 12 = 8.10 ± 0.03 (Garnett et al. 1997) or log(O/H)+12 = 8.28 ± 0.04 (Berg et al. 2013). This is in the range where red $[3.6]–[4.5]$ colors become more common for dwarf galaxies (Smith & Hancock 2009). No metallicities are available for our hinge clumps at present.

In the right panel of Figure 3, we plot the $[3.6]–[24]$ color against the 24 μm luminosity. A rough correlation is seen in this plot, such that the clumps with the highest luminosity tend to be redder. The large scatter in this plot is likely due in part to the fact that the apertures cover different physical sizes in the different galaxies. Note that the NGC 2403 and Magellanic Cloud luminosities are lower on average, due to the smaller areas covered. The LMC and SMC apertures range from 105 pc to 450 pc (Lawton et al. 2010).

6. X-RAY VERSUS UV/IR COLORS

In Figure 4 we plot the observed (uncorrected for dust attenuation) log $L_X/L_{24\mu m}$ against $[3.6]–[24]$ and against NUV – [24], for the hinge clumps with Chandra data available. In this figure we compare with both the star forming knots in the Antennae as well as the star forming regions within the normal spiral NGC 2403. For the regions in NGC 2403, we used the diffuse X-ray fluxes from Yukita et al. (2010), which were obtained from the Chandra map after bright point sources were removed. This plot shows that the NGC 2403 regions have lower observed $L_X/L_{24\mu m}$ for a given $[3.6]–[24]$ color than either the hinge clumps or the positions in the Antennae. They also have lower [NUV]–[24] values, indicating lower extinction. Some of the hinge clumps lie in the region populated by the Antennae points, while some are lower on this plot. The NGC 2207 clump lies between Antennae overlap regions 3 and 4 in these plots, with large $[3.6]–[24]$ and low observed $L_X/L_{24\mu m}$.

Correcting these X-ray fluxes for dust attenuation is critical, given the large absorbing columns toward some of these regions implied by their red NUV – [24] colors. The correction for dust attenuation is discussed further in Section 7.3.

Two of the hinge clumps with X-ray point sources (Arp 270-1 and Arp 240-4) likely host ULXs, as their X-ray luminosities are very high compared to other regions with similar $[3.6]–[24]$ colors (Figure 4). Alternatively, these regions may contain two or more lower luminosity HMXBs very close together. The third X-ray point source, Arp 240-3, has a location on this plot similar to that of the clumps resolved by Chandra, thus its X-ray emission may be due to a compact young star formation region rather than a ULX. This is consistent with its intrinsically soft X-ray spectrum (Section 3.3).

7. STELLAR POPULATION SYNTHESIS MODELS

7.1. Overview

We compared the large aperture GALEX/SDSS broadband UV/optical colors of these clumps with population synthesis models to determine the ages of their stellar populations and their dust attenuations. We used the large aperture HST photometry as a check on these fits. We did not use the 2MASS near-infrared or Spitzer 3.6 and 4.5 μm fluxes in these fits, although this light may also be dominated by starlight. This point is discussed further in Section 7.2. We obtained a second independent estimate of the stellar age from the Hα equivalent width.

For this analysis we assume a single instantaneous burst. As discussed below, for some of these clumps more than one generation of stars may be present. In these cases, the ages we derive from the single-burst models are a luminosity-weighted average age for the stars in the clump. As in our earlier studies (Smith et al. 2008; Hancock et al. 2009; Lapham et al. 2013), we use the Starburst99 population synthesis code (Leitherer et al. 1999) and include the Padova asymptotic giant branch stellar models (Vazquez & Leitherer 2005). We assume a Kroupa IMF and solar metallicity. We integrated the model spectra over the GALEX and SDSS bandpasses, including the Hα line from Starburst99 in the model spectra as well as other optical emission lines, derived using the prescription given by Anders & Fritze-v. Alvensleben (2003) for solar metallicity star forming regions. We used the Calzetti et al. (1994) starburst dust attenuation law.

The best fit ages and dust reddening $E(B-V)$ values from the broadband photometry are given in Table 11, along with uncertainties on these values. These were computed using a chi squared ($\chi^2$) minimization calculation as in our earlier studies. For these fits, we only used the filters with reliable detections; upper limits were ignored. When available, we used the FUV–NUV, NUV–g, u–g, g–r, r–i, and i–z colors for fitting. In calculating the $\chi^2$ values, in addition to the statistical errors, we included additional uncertainties in the colors due to
uncertainties in the GALEX aperture corrections (see Table 4) and in background subtraction. To estimate the uncertainties due to background subtraction, we calculated colors using an alternative second sky annulus with an inner radius of 8″ and an outer radius of 14″. To estimate the uncertainties in the best fit parameters, we used the Δχ² method (Press et al. 1992) to determine 68.3% confidence levels for the parameters. In Table 11, we provide the reduced χ², equal to χ²/(N − 2), where N is the number of colors used in the fit.

As can be seen in Table 11, for some of the clumps the fits are quite good. For a few, however, the χ² values indicate a very poor fit (e.g., Arp 82, Arp 240-1, Arp 240-3, and especially Arp 256). This suggests that more than one age of stars are present. Two or more bursts of star formation may have occurred in the region, or the star formation continued over an extended time period.

We obtain a second independent estimate of the age of the stellar population using the Hα equivalent width and assuming an instantaneous burst. These ages are tabulated in Table 12. Except for regions Arp 240-1, Arp 256-1, Arp 270-1, and Arp 270-3, these ages are younger than the ages derived from the broadband UV/optical fluxes (Table 11). Such differences in derived ages have been found earlier for some knots of star formation in Arp 284 and Arp 107 (Peterson et al. 2009; Lapham et al. 2013), and provide additional support for the idea that these hinge clumps host a range of stellar ages. Ages from Hα equivalent widths tend to be biased toward the younger populations in a region, while the broadband ages are weighted toward the somewhat older stars that sometimes dominate the UV/blue light from star forming regions. The comparison of these two age estimates illustrates the uncertainties in age determinations via population synthesis.

### 7.2. SED Plots and Near-IR Excesses

In Figures 5–7, we plot the large-aperture spectral energy distributions (SEDs) for these clumps, including the GALEX, SDSS, Spitzer, 2MASS, and HST large aperture photometry. On these plots, we overlay the best fit Starburst99 single-population models from the broadband data. As an indication of the uncertainties in these models, in these figures we also plot models with the best fit reddening and the best fit age ± the 1σ uncertainty in the age. As can be seen from these plots, in some cases a single-burst model does not provide a good match to the SED. For NGC 2207, which lacks SDSS data, we do not provide a best fit model; however, comparison to the other SEDs shows that it has quite red colors, consistent with high obscuration (see Section 7.3).

As shown in Figures 5–7, for some of the clumps the Spitzer 3.6 μm and 4.5 μm fluxes are higher than predicted by the best fit single-burst models, which do not include dust emission. In some cases, the HST or 2MASS near-infrared fluxes are also higher than expected from our single-burst models. This is additional evidence for two or more generations of stars or

### Table 11

| Clump  | Age (Myr) | E(B − V) (mag) | Stellar Mass (M☉) | Reduced Chi Squared | Colors Used |
|--------|-----------|----------------|-------------------|--------------------|-------------|
| Arp 82-1 | 100 ± 21  | 0.00 ± 0.06 | 2.5 × 10⁷ | 11.5 | FUV − NUV, NUV − g, u − g, g − r, r − i, i − z |
| Arp 240-1 | 6 ± 1 | 0.54 ± 0.01 | 45.1 × 10⁷ | 10.9 | NUV − g, u − g, r − i, i − z |
| Arp 240-2 | 150 ± 1 | 0.14 ± 0.06 | 203.3 × 10⁷ | 6.8 | NUV − g, u − g, r − i, i − z |
| Arp 240-3 | 150 ± 101 | 0.14 ± 0.10 | 95.5 × 10⁷ | 14.0 | NUV − g, u − g, r − i, i − z |
| Arp 240-4 | 45 ± 16 | 0.28 ± 0.06 | 111.0 × 10⁷ | 2.3 | NUV − g, u − g, r − i, i − z |
| Arp 240-5 | 70 ± 26 | 0.56 ± 0.12 | 338.4 × 10⁷ | 4.3 | NUV − g, u − g, r − i, i − z |
| Arp 256-1 | 6 ± 1 | 0.54 ± 0.06 | 21.8 × 10⁷ | 32.8 | FUV − NUV, NUV − g, u − g, g − r, r − i, i − z |
| Arp 270-1 | 5 ± 1 | 0.28 ± 0.12 | 0.2 × 10⁷ | 7.1 | FUV − NUV, NUV − g, u − g, r − i, i − z |
| Arp 270-2 | 70 ± 31 | 0.00 ± 0.00 | 0.7 × 10⁷ | 1.0 | FUV − NUV, NUV − g, u − g, r − i, i − z |
| Arp 270-3 | 6 ± 20 | 0.26 ± 0.26 | 0.2 × 10⁷ | 1.3 | FUV − NUV, NUV − g, u − g, r − i, i − z |
| Arp 270-4 | 50 ± 21 | 0.00 ± 0.28 | 1.7 × 10⁷ | 0.6 | FUV − NUV, NUV − g, u − g, r − i, i − z |

### Figure 5

Broadband large aperture GALEX/SDSS/Spitzer/HST/2MASS UV/optical/IR spectral energy distributions (SEDs) of some of the clumps in the sample (green filled squares). The black solid curve is the best fit model. The blue dashed curve is the burst model with the best fit reddening, and an age 1σ less than the best fit age. The red dotted curve is the burst model with the best fit reddening, and an age 1σ more than the best fit age. The plotted error bars only include statistical errors. Note that the fits only include the GALEX/SDSS UV/optical photometry; we extend the model stellar component to longer wavelengths to compare with the Spitzer and near-infrared data to search for excesses in those bands (see Section 7.2).

(A color version of this figure is available in the online journal.)
ongoing star formation. Alternatively, as noted in Section 5, there may be excess flux in these bands above the stellar continuum due to hot dust or to interstellar gas emissions (see Smith & Hancock 2009).

Instead of instantaneous bursts, a better model of the star formation history in these clumps might be prolonged star formation (continuous for an extended period, then shut off), or an exponentially decaying SFR (e.g., Boquien et al. 2010). As discussed in Appendix B, regions 3 and 4 in the Antennae galaxy each host stars with a range of ages; our hinge clumps, which cover even larger physical sizes than the Antennae photometry, may also contain a range of stellar ages. As an approximation, in Lapham et al. (2013) we explored models with two instantaneous bursts for fitting clumps of star formation within Arp 107. These provide better fits to the SEDs than single bursts, but we were unable to constrain the parameters of the fit well, as we were able to find multiple models with very different parameters that fit the data equally well. In general, adding more parameters to the fitting routine by allowing more than one stellar age increases the uncertainties in the derived parameters. Thus in this work, we focus on single-burst models, and emphasize that the derived ages are luminosity-weighted stellar ages, averaged over the timescale of the burst, and the star formation was likely prolonged rather than truly instantaneous.

It is also possible to include the mid-infrared photometry in the population synthesis modeling (e.g., Noll et al. 2009; Boquien et al. 2010). However, this also adds additional parameters to the model, including the dust properties and the location of the dust relative to the stars. Thus in this work we derive ages from only the UV/optical data.

### 7.3. Attenuation

In Table 11, we provide the $E(B-V)$ estimates determined from the broadband Starburst99 modeling. We obtained a second independent estimate of the absorption using the ratio of the 24 $\mu$m luminosity to $H\alpha$ luminosity (Table 12). For this calculation, we used the empirically determined relationship between the absorption in the $H\alpha$ emission line and the 24 $\mu$m emission obtained by Kennicutt et al. (2007) for star forming regions within M51: $A_{H\alpha} = 2.5\log[1 + 0.038L_{24}/L_{H\alpha}]$. As noted by these authors, there is considerable scatter in this relation, and for a given star forming region the true relation likely depends upon the geometry, the stellar types, and the age. In the hinge clumps, we expect an even larger scatter in the relationship, as we are likely averaging over a range of extinctions within the beam. We converted from $A_{H\alpha}$ to hydrogen column density using $A_{H\alpha} = 0.82A_V$ and the Calzetti et al. (2000) starburst total to selective attenuation ratio $R_V = A_V/E(B-V) = 4.05$.

For some of the clumps, the absorption derived from $A_{H\alpha}$ agrees reasonably well with that obtained from the broadband photometry. For others, the $H\alpha$-derived estimates are higher than that inferred from the broadband photometry. This difference may be caused by a range of ages and extinctions in the clumps, with the younger stars being more obscured. In starburst galaxies, the ionized gas tends to be more obscured than the starlight on average (e.g., Calzetti 2001). For the region in NGC 2207, our estimate of $A_V = 4.1$ from $L_{24}/L_{H\alpha}$ (Table 12) is consistent with the Kaufman et al. (2012) limit of $A_V \leq 4.9$ determined from the ratio of the 6 cm flux to that in $H\alpha$.

As mentioned in Section 3.3, we are not able to determine X-ray absorptions directly from the Chandra data itself.

### Table 12

Reddening and Ages from the $H\alpha$ Data, and Related Quantities

| Clump         | $A_V$ (mag) | $E(B-V)$ (mag) | $N_H$ (10$^{21}$ cm$^{-2}$) | Age (Myr) | Stellar Mass ($M_\odot$) (Corrected) | $L_X/L_{H\alpha}$ (Corrected) (erg s$^{-1}$)/(M$_\odot$ yr$^{-1}$)) | $n_e\sqrt{\mathcal{F}}$ (cm$^{-3}$) | XPE $^{b}$ |
|---------------|------------|----------------|-----------------------------|-----------|--------------------------------------|---------------------------------------------------------------|-----------------------------------|-----------|
| Arp 82-1      | 1.34 ± 0.02| 0.33 ± 0.01    | 1.93 ± 0.02                 | 5.4 ± 0.2 | 0.7 × 10$^{7}$                       | ...                                                           | ...                               | ...       |
| Arp 240-1     | 1.59 ± 0.02| 0.39 ± 0.01    | 2.27 ± 0.02                 | 6.1 ± 0.5 | 35.2 × 10$^{7}$                      | 0.26                                                          | 4.1 × 10$^{29}$                   | 0.035     | 0.0022    |
| Arp 240-2     | 1.93 ± 0.02| 0.48 ± 0.01    | 2.76 ± 0.02                 | 5.8 ± 0.3 | 27.5 × 10$^{7}$                      | 0.053                                                         | 4.2 × 10$^{29}$                   | 0.077     | 0.0053    |
| Arp 240-3     | 2.41 ± 0.02| 0.59 ± 0.01    | 3.45 ± 0.02                 | 5.5 ± 0.1 | 25.7 × 10$^{7}$                      | 0.038                                                         | 6.2 × 10$^{29}$                   | 0.297     | 0.0083    |
| Arp 240-4     | 1.71 ± 0.02| 0.42 ± 0.01    | 2.45 ± 0.02                 | 6.1 ± 0.5 | 22.0 × 10$^{7}$                      | 0.378                                                         | 70.9 × 10$^{29}$                  | 0.850     | 0.0319    |
| Arp 240-5     | 3.27 ± 0.02| 0.81 ± 0.01    | 4.69 ± 0.02                 | 6.1 ± 0.5 | 63.0 × 10$^{7}$                      | 0.069                                                         | 16.5 × 10$^{29}$                  | 0.038     | 0.0058    |
| Arp 256-1     | 1.69 ± 0.02| 0.42 ± 0.01    | 2.42 ± 0.02                 | 6.3 ± 0.5 | 17.6 × 10$^{7}$                      | 0.076                                                         | 17.3 × 10$^{29}$                  | 0.098     | 0.0065    |
| Arp 270-1     | 0.97 ± 0.02| 0.24 ± 0.01    | 1.39 ± 0.02                 | 5.9 ± 0.4 | 0.1 × 10$^{7}$                       | 0.893                                                         | 147.2 × 10$^{29}$                 | 0.526     | 0.0795    |
| Arp 270-2     | 1.63 ± 0.02| 0.40 ± 0.01    | 2.33 ± 0.02                 | 6.2 ± 0.5 | 0.2 × 10$^{7}$                       | ≲0.076                                                       | ≲15.9 × 10$^{29}$                | ...       | 0.0060    |
| Arp 270-3     | 0.98 ± 0.02| 0.24 ± 0.01    | 1.40 ± 0.02                 | 5.7 ± 0.1 | 0.2 × 10$^{7}$                       | ≲0.031                                                       | ≲8.9 × 10$^{29}$                 | ...       | 0.0045    |
| Arp 270-4     | 0.73 ± 0.02| 0.18 ± 0.01    | 1.04 ± 0.02                 | 5.3 ± 0.2 | 0.5 × 10$^{7}$                       | ≲0.007                                                       | ≲2.1 × 10$^{29}$                 | ...       | 0.0024    |
| NGC 2207-1    | 4.12 ± 0.02| 1.02 ± 0.01    | 5.90 ± 0.02                 | 5.7 ± 0.2 | 4.3 × 10$^{7}$                       | 0.064                                                         | 15.1 × 10$^{29}$                  | 0.033     | 0.0074    |

Notes.

$^{a}$ From $A_{H\alpha} = 2.5\log[1 + 0.038L_{24}/L_{H\alpha}]$ (Kennicutt et al. 2007).

$^{b}$ Using $A_V/E(B-V) = 4.05$ (Calzetti et al. 2000).

$^{c}$ Using $N_H$ (cm$^{-2}$) = 5.8 × 10$^{21}$E($B-V$) from Bohlin et al. (1978).

$^{d}$ From the $H\alpha$ equivalent width, assuming an instantaneous burst.

$^{e}$ Obtained by scaling the observed $i$ band flux (or HST F814W flux, if no SDSS $i$ image available) to Starburst99 models assuming an instantaneous burst, using the age determined from the $H\alpha$ equivalent width and the absorption determined from the $H\alpha/24\mu$m flux ratio.

$^{f}$ The ratio of the 0.3–8 keV X-ray luminosity $L_X$ to the $H\alpha$ luminosity, corrected for extinction using the $H\alpha/24\mu$m flux ratio as described in the text.

$^{g}$ The ratio of the extinction-corrected 0.3–8 keV luminosity to the SFR. When both estimates of SFR are available, the average value is used.

$^{h}$ Electron number density $n_e \times \sqrt{\mathcal{F}}$, where $\mathcal{F}$ is the volume filling factor (see the text for details). Note that these are not relevant if the X-ray source is a ULX, which is likely for Arp 270-1 and Arp 240-4 (see the text).

$^{i}$ X-Ray production efficiency $= L_X/L_{\text{Mech}}$. 
We therefore correct the X-ray data for absorption using column densities obtained from the $L_{24}/L_{\text{He}}$ ratio, as it is likely more valid for the ionized gas than values obtained from broadband photometry. We first converted from $E(B-V)$ to hydrogen column density using $N_H(\text{cm}^{-2}) = 5.8 \times 10^{21} E(B-V)$ (Bohlin et al. 1978). These estimates range from $N_H = 1-6 \times 10^{21} \text{cm}^{-2}$ (see Table 12). We emphasize that these estimates are quite uncertain, since the X-ray-emitting gas may be less obscured than the H$\alpha$-emitting ionized gas within H$\text{II}$ regions. However, these estimates are similar to the absorbing column densities found by Mineo et al. (2012b), who fit X-ray spectra of the global diffuse X-ray emission of a sample of nearby late-type star forming galaxies. Obtaining higher quality X-ray data for our hinge clumps would be very valuable to better constrain the X-ray absorption.

Using these estimates of the absorbing column, we next determined the ratio of the attenuation in the 0.3–8 keV X-ray band to the hydrogen column density $A_X/N_H$ using the wabs routine in the XSPEC$^{11}$ software (this uses the Wisconsin absorption cross-sections, e.g., Morrison & McCammon 1983). The $A_X/N_H$ ratio depends on both the X-ray spectrum and the hydrogen column density. For this calculation, we assumed a 0.3 keV thermal spectrum, thus $A_X/N_H$ varies between $7.19 \times 10^{-22} \text{mag cm}^2$ for $N_H = 3 \times 10^{20} \text{cm}^{-2}$ and $A_X/N_H = 2.73 \times 10^{-22} \text{mag cm}^2$ for $N_H = 2 \times 10^{22} \text{cm}^{-2}$.

$^{11}$ http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/index.html

These corrections have been applied to the observed X-ray fluxes. In Table 9, we provide absorption-corrected X-ray luminosities for each hinge clump. We provide both the luminosity of the central source, as well as luminosities within the larger 5″ radius aperture, assuming the same correction factor for both. These corrections are generally multiplicative factors of 2–5, with larger correction factors for the two most obscured regions Arp 240-5 and NGC 2207 (factors of 9 and 13, respectively). We emphasize that these corrected luminosities are quite uncertain due to uncertainties in both the correction method and in the fluxes themselves.

The absorption-corrected X-ray luminosities $L_X$ (0.3–8 keV) of the eight detected hinge clumps (Table 9) are all greater than $10^{39} \text{erg s}^{-1}$, with seven greater than $10^{40} \text{erg s}^{-1}$. For the three hinge clumps that were undetected by Chandra, we provide upper limits in Table 9 assuming the reddening from the $L_{24}/L_{\text{He}}$ ratio.

The most X-ray luminous region in Table 9 is the point source in clump 4 of Arp 240W, which has a corrected 0.3–8 keV luminosity of $\sim 2 \times 10^{41} \text{erg s}^{-1}$. The absorption correction for this source may be overestimated by the above method, if the source has an intrinsically hard spectrum. However, even without any correction at all, the luminosity of this source is high, $5 \times 10^{40} \text{erg s}^{-1}$. Obtaining higher S/N X-ray spectroscopy of this source would be very valuable, to better determine the absorbing column and therefore the intrinsic

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**Figure 6.** Broadband large aperture GALEX/SDSS/Spitzer/HST/2MASS UV/optical/IR spectral energy distributions (SEDs) of some of the clumps in the sample (green filled squares). The black solid curve is the best fit single-age instantaneous burst model. The blue dashed curve is the burst model with the best fit reddening, and an age $1 \sigma$ less than the best fit age. The red dotted curve is the burst model with the best fit reddening, and an age $1 \sigma$ more than the best fit age. The plotted error bars only include statistical errors. Note that the fits only include the GALEX/SDSS UV/optical photometry; we extend the model stellar component to longer wavelengths to compare with the Spitzer and near-infrared data to search for excesses in those bands (see Section 7.2).

(A color version of this figure is available in the online journal.)

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**Figure 7.** Broadband large aperture GALEX/SDSS/Spitzer/HST/2MASS UV/optical/IR spectral energy distributions (SEDs) of some of the clumps in the sample (green filled squares). The black solid curve is the best fit single-age instantaneous burst model. The blue dashed curve is the burst model with the best fit reddening, and an age $1 \sigma$ less than the best fit age. The red dotted curve is the burst model with the best fit reddening, and an age $1 \sigma$ more than the best fit age. The plotted error bars only include statistical errors. Note that the fits only include the GALEX/SDSS UV/optical photometry; we extend the model stellar component to longer wavelengths to compare with the Spitzer and near-infrared data to search for excesses in those bands (see Section 7.2). Since no SDSS data is available for NGC 2207, we do not provide a best fit model for that region.

(A color version of this figure is available in the online journal.)
luminosity. At a luminosity of \( \sim 2 \times 10^{41} \text{ erg s}^{-1} \), this would be one of the most luminous ULXs known, and therefore a possible intermediate mass black hole.

### 7.4. Stellar Masses

For both methods of determining ages and extinctions, we estimated stellar masses for the clumps (Tables 11 and 12). As expected, the masses derived using the Hα equivalent widths are sometimes lower than those obtained from the broadband photometry, since the inferred ages are younger. We note that stellar masses derived by scaling directly from the K and 3.6 μm photometry (e.g., Bell & de Jong 2001; Bell et al. 2003; Into & Portinari 2013) are considerably larger (factors of 2–25 times larger) than the masses obtained from individual fitting of the UV/optical broadband photometry. These scaling factors are intended for galaxies as a whole rather than individual star forming regions within galaxies, and, as discussed by Gallazzi & Bell (2009), they may over-estimate the stellar mass in systems undergoing recent bursts. Even when population synthesis fitting is done, the stellar masses are quite uncertain (up to a factor of five; Smith et al. 2008).

### 8. \( L_X \) VERSUS STAR FORMATION PROPERTIES

#### 8.1. \( L_X / SFR \) Ratios: The Hinge Clumps, Antennae, and NGC 2403

In Table 12 we provide \( L_X / L_{Ha} \) and \( L_X / SFR \) ratios for each hinge clump, corrected for extinction using the Hα/24 μm-derived values. For these calculations, we use the X-ray fluxes within a 5″ radius. Two of the hinge clumps (Arp 240-4 and Arp 270-1) have much higher values than the rest, supporting the idea that they are ULXs. For the remaining clumps, this table shows that the X-ray luminosity is not perfectly correlated with SFR, since there is a scatter of about a factor of four in these ratios.

For the Antennae and NGC 2403 we calculated \( L_X / SFR \) ratios using the same procedure. As with the hinge clumps, for both the Antennae and NGC 2403 it is difficult to constrain the internal extinction from the X-ray spectra alone (e.g., Metz et al. 2004; Yukita et al. 2010). We therefore estimate the dust absorption within these regions using the 24 μm and Hα fluxes within our apertures, as we did for the hinge clumps. For the Antennae these range from \( A_V = 0.67 \) to 3.23, with region 4 having the highest value. For the NGC 2403 regions, the implied absorption is much smaller than for the Antennae and the hinge clumps, with \( A_V \) between 0.08 and 0.50.

Excluding the regions with bright X-ray point sources, the median extinction-corrected \( L_X / SFR \) for the Antennae areas is \( 5.7 \times 10^{39} \text{ erg s}^{-1} / (M_\odot \text{ yr}^{-1}) \) using the Hα+24 μm estimate of SFR. For the NUV+24 μm method, the median \( L_X / SFR \) is \( 8.3 \times 10^{39} \text{ erg s}^{-1} / (M_\odot \text{ yr}^{-1}) \) for the Antennae regions. These are similar to the ratios for the non-ULX hinge clumps (Table 12).

For NGC 2403, the absorption-corrected \( L_X / SFR \) ratios have a median value of \( 6 \times 10^{38} \text{ erg s}^{-1} / (M_\odot \text{ yr}^{-1}) \) for the Hα+24 μm method and \( 4 \times 10^{38} \text{ erg s}^{-1} / (M_\odot \text{ yr}^{-1}) \) for the NUV+24 μm method. The latter value agrees reasonably well with those of the hinge clumps, while the ratio determined using the Hα+24 μm method is somewhat lower.

#### 8.2. \( L_X / SFR \) Ratios from Other Studies

For a sample of nearby spirals and irregulars, Mineo et al. (2012b) extracted the diffuse X-ray emission and compared with the SFR. Their best fit value for the ratio of the extinction-corrected 0.3–10 keV X-ray luminosity from hot gas to the SFR is \( L_X(0.3–10 \text{ keV}) / SFR = (7.3 \pm 1.3) \times 10^{39} \text{ erg s}^{-1} / (M_\odot \text{ yr}^{-1}) \). Given their somewhat different definition of SFR, their different energy range, and their different method of correcting for internal extinction, their results are consistent with our values for the hinge clumps (Table 12). They also agree well with our values for the Antennae regions dominated by diffuse X-ray emission (Section 8.1). The Mineo et al. (2012b) ratios are somewhat higher than the mean \( L_X / SFR \) of \( 1.4 \times 10^{39} \text{ erg s}^{-1} / (M_\odot \text{ yr}^{-1}) \) found by Li & Wang (2013) for the coronal X-ray emission from 53 edge-on disk galaxies.

In Smith et al. (2005), we collated X-ray luminosities, extinction-corrected Hα luminosities, and published ages for 20 H II regions within Local Group galaxies and the nearby galaxies M101 and NGC 4303. Regions with ages \( < 3 \text{ Myr} \) (before supernovae turn on) show dramatically lower \( L_X / SFR \) ratios than older regions. The younger H II regions have a median \( L_X / SFR \) of \( 3.4 \times 10^{38} \text{ erg s}^{-1} / (M_\odot \text{ yr}^{-1}) \). This contrasts sharply with the median value of the rest of the regions of \( 2 \times 10^{39} \text{ erg s}^{-1} / (M_\odot \text{ yr}^{-1}) \). Our hinge clumps have ratios similar to those of the older H II regions, indicating that supernova activity has begun in the hinge clumps.

In Smith et al. (2005), we found extended X-ray emission from four H II regions in the primary disk of the interacting pair Arp 284 using Chandra. Using the same conversion as above, for these regions we find \( L_X / SFR \) between \( 8 \times 10^{39} \text{ erg s}^{-1} / (M_\odot \text{ yr}^{-1}) \) and \( 4 \times 10^{40} \text{ erg s}^{-1} / (M_\odot \text{ yr}^{-1}) \). These are similar to the values for our hinge clumps.

From these comparisons, we conclude that the hinge clumps are producing X-rays at a rate relative to the SFR similar to those of star forming regions in other galaxies.

#### 8.3. HMXBs

The intrinsically soft X-ray spectra of most of the hinge clumps argue that this emission is dominated by hot gas. However, a fraction of the observed X-ray emission may be due to the combined light of multiple unresolved X-ray point sources. For star forming regions, this additional component is likely dominated by HMXBs, as the number of HMXBs in a galaxy is correlated with the SFR (Grimm et al. 2003; Gilfanov et al. 2004; Persic et al. 2004; Mineo et al. 2012a). Other kinds of X-ray-emitting objects, such as young stellar objects, hot stars, and low mass X-ray binaries, are expected to be less important to the observed X-ray emission from strongly star forming systems (e.g., Bogdán & Gilfanov 2011; Mineo et al. 2012b). HMXBs are associated with populations with ages between 20 and 70 Myr (Antoniou et al. 2010; Williams et al. 2013). These ages are consistent with our estimates of the average stellar ages in some of the hinge clumps from the broadband UV/optical photometry. Thus sufficient time may have passed to produce HMXBs in at least some of our hinge clumps.

To estimate the contributions from HMXBs to the X-ray luminosities of the hinge clumps, we use the relation found by Mineo et al. (2012a) for HMXBs in nearby star forming galaxies of \( L(0.5–8 \text{ keV}) / \text{HMXBs} = \text{SFR} \times (2.6 \times 10^{39} \text{ erg s}^{-1}) \). As discussed at length by Mineo et al. (2012a), this relation agrees well with relations found by Grimm et al. (2003) and Ranalli et al. (2003), after conversion to the same energy range and SFR definitions. Excluding the two candidate ULXs, this relation implies that about 15%—30% of the X-ray light from the hinge clumps comes from HMXBs, with an estimated fraction of 40%
for clump 1 in Arp 240. These estimates are very uncertain, as there is a lot of scatter in the SFR–HMXB relation (Mineo et al. 2012a), and this relation was derived by averaging over entire galaxies, thus it is not necessarily appropriate for individual star forming regions. However, it provides a very approximate estimate, which supports our conclusion based on the soft X-ray spectra that in most cases the X-ray emission from these clumps is dominated by radiation from hot gas rather than HMXBs.

As noted earlier, the absorption-corrected X-ray luminosity of clump 4 in Arp 240 \( (2 \times 10^{41} \text{ erg s}^{-1}) \) is higher than expected for HMXBs, thus it may host an intermediate mass black hole. Alternatively, it may contain multiple luminous HMXBs. Its \( L_X/\text{SFR} \) of \( 7 \times 10^{40} \text{ erg s}^{-1} \( (M_\odot \text{ yr}^{-1})^{-1} \) (Table 12) is more than an order of magnitude higher than that found by Mineo et al. (2012a) for HMXBs in nearby spiral galaxies. If this X-ray emission is due to a collection of HMXBs, this region is either unusually rich in HMXBs per SFR compared to other systems, or its SFR was considerably higher in the very recent past. However, our \( L_X \) and NUV estimates of SFR for this clump agree well \( (2.8 \, M_\odot \text{ yr}^{-1} \) and \( 2.3 \, M_\odot \text{ yr}^{-1} \) (Table 12), although \( L_X \) and NUV are sensitive to star formation on different timescales \( (\sim 10 \text{ Myr} \) and \( \sim 200 \text{ Myr} \), respectively; Kennicutt & Evans 2012). Thus there is no evidence for a dramatic drop in SFR in this region in the \( \lesssim 70 \text{ Myr} \) timescale for HMXB production. The total stellar mass of this clump \( (2 \times 10^8 \) to \( 1 \times 10^9 \, M_\odot \) (Tables 11 and 12) could be produced by a steady rate of \( \sim 2-3 \, M_\odot \text{ yr}^{-1} \) over \( \sim 200 \text{ Myr} \), without requiring a significantly higher rate in the recent past, but that steady rate would not be enough to produce such a high HMXB luminosity today.

### 8.4. ULXs

A related question is whether the hinge clumps host ULXs at the rate expected from their SFRs, where a ULX is defined to be a point source with \( L_X \gtrsim 10^{39} \text{ erg s}^{-1} \). As noted earlier, most ULXs with luminosities between \( 10^{39} \text{ erg s}^{-1} \) and \( 10^{41} \text{ erg s}^{-1} \) are likely high luminosity HMXBs. Out of our 12 hinge clumps, three host point sources with \( L_X \gtrsim 10^{39} \text{ erg s}^{-1} \), however, the source in Arp 240-3 has a likely thermal spectrum, and as discussed below, its X-ray emission is probably dominated by hot gas. The other two point sources, Arp 240-4 and Arp 270-1, are candidate ULXs.

To determine whether the frequency of ULXs in hinge clumps relative to the SFR is consistent with those of galaxies as a whole, we compare to our statistical studies of ULXs in normal galaxies (Swartz et al. 2004, 2011) and strongly interacting galaxies from the Arp Atlas (Smith et al. 2012). In those studies, we determined the number of ULXs per far-infrared luminosity \( L_{\text{FIR}} \) for various samples of galaxies. To compare with these studies, we estimated \( L_{\text{FIR}} \) for the hinge clumps using the Calzetti et al. (2005) relation between the 8 \( \mu \text{m} \) and 24 \( \mu \text{m} \) fluxes and the total infrared luminosity \( L_{\text{IR}} \), and used the approximate relation between \( L_{\text{FIR}} \) and \( L_{\text{IR}} \) of 0.55\( L_{\text{IR}} \) from Helou et al. (1988).

For all but one of our sample galaxies, the \( L_X/L_{\text{IR}} \) ratio is insufficient to detect all ULXs down to the limiting luminosity of \( L_X \gtrsim 10^{38} \text{ erg s}^{-1} \). However, the \( L_X/L_{\text{IR}} \) data for all of our systems have sufficient sensitivity to detect ULXs more luminous than \( L_X \gtrsim 10^{40} \text{ erg s}^{-1} \). We can compare the number of ULXs above \( L_X \gtrsim 10^{40} \text{ erg s}^{-1} \) with the combined estimated far-infrared luminosity of all of the sample hinge clumps, \( 2.2 \times 10^{42} \text{ erg s}^{-1} \). We find only one candidate ULX in our hinge clump sample above \( 10^{40} \text{ erg s}^{-1} \), Arp 240-4. This gives a ratio of the number of ULXs above \( 10^{40} \text{ erg s}^{-1} \) per far-infrared luminosity of \( N_{\text{ULX}}/L_{\text{FIR}} = 4.6 \times 10^{-45} \text{ erg s}^{-1}^{-1} \). This is consistent within the uncertainties with the ratios found for spiral galaxies of \( N_{\text{ULX}}/L_{\text{FIR}} = 6.7 \pm 2.9 \times 10^{-45} \text{ erg s}^{-1}^{-1} \) (Swartz et al. 2004) or \( 9.4 \pm 2.2 \times 10^{-45} \text{ erg s}^{-1}^{-1} \) (Swartz et al. 2011). Interestingly, the Arp sample appears to have a deficiency of ULXs in this luminosity range, with \( N_{\text{ULX}}/L_{\text{FIR}} = 9.6 \times 10^{-46} \text{ erg s}^{-1}^{-1} \) (Smith et al. 2012). This may be because the Arp sample includes a number of ultra-luminous infrared galaxies (ULIRGs), which dominate the combined far-infrared luminosity of the sample yet have relatively few ULXs. ULXs may be more obscured in ULIRGs, leading to a deficiency in the observed number of ULXs in this sample; alternatively, a hidden active galactic nucleus may be contributing to \( L_{\text{FIR}} \) in the ULIRGs (Smith et al. 2012). Hinge clumps appear to be forming \( L_X \gtrsim 10^{40} \text{ erg s}^{-1} \) ULXs at a rate relative to their SFR similar to spirals. They do not appear to be deficient in these ULXs relative to the SFR, in contrast to ULIRGs.

For Arp 270 is the \( L_X/L_{\text{IR}} \) ratio for all ULXs down to \( 10^{38} \text{ erg s}^{-1} \). The combined estimated \( L_{\text{FIR}} \) for the four hinge clumps in Arp 270 is \( 1.5 \times 10^{43} \text{ erg s}^{-1} \), giving \( N_{\text{ULX}}/L_{\text{FIR}} = 6.6 \times 10^{-43} \text{ erg s}^{-1}^{-1} \) for \( L_X \gtrsim 10^{40} \text{ erg s}^{-1} \). This is considerably higher than the \( N_{\text{ULX}}/L_{\text{FIR}} \) ratio for spirals of \( 6.5 \pm 0.7 \times 10^{-44} \text{ erg s}^{-1}^{-1} \) (Swartz et al. 2004) or \( 5.3 \pm 0.5 \times 10^{-44} \text{ erg s}^{-1}^{-1} \) (Swartz et al. 2011). This difference may simply be due to small number statistics; alternatively, the candidate ULX in Arp 270-1 may be a background source rather than a true ULX.

In the ULX luminosity range \( \gtrsim 10^{40} \text{ erg s}^{-1} \), the \( N_{\text{ULX}}/L_{\text{FIR}} \) ratio for Arp systems is similar to that of spirals, \( 7.6 \pm 1.3 \times 10^{-44} \text{ erg s}^{-1}^{-1} \) (Smith et al. 2012). The subset of Arp systems in the Smith et al. (2012) sample that have \( L_X/L_{\text{IR}} \) point sources contains fewer high \( L_{\text{FIR}} \) systems than the larger Arp sample with \( L_{\text{FIR}} \) sensitivity with \( L_{\text{FIR}} \) similar to spirals in their ULX populations.

### 8.5. Electron Densities in the Hot Gas

To estimate the electron number density \( n_e \) in the hot gas within the hinge clumps, we used the angular extents of the central X-ray source (Table 9) to calculate the volume of X-ray-emitting gas, assuming an ellipsoidal shape with the third axis equal to the average of the other two dimensions. For the NGC 2403 regions, we estimated the volume using the radii of the X-ray-emitting regions obtained by Yukita et al. (2010), and assumed a spherical shape. For the Antennae, we estimated angular extents of the diffuse X-ray emission for each region from the co-added \( L_X \) map, assuming an ellipsoidal shape as for the hinge clumps. For each of these regions, we calculated \( n_e \sqrt{f} \), where \( f \) is the volume filling factor (Table 12). We used standard cooling functions (McKee & Cowie 1977; McCray 1987) and assumed thermal emission with a temperature \( kT \) of 0.3 keV. We used the \( L_X \) of the central source for these calculations rather than the large aperture luminosity. We emphasize that these estimates of \( n_e \sqrt{f} \) are very uncertain, because of uncertainties in the measured angular extent of the X-ray emission which is a function of sensitivity, as well as lack of information about the line-of-sight path length through the ionized region and the three-dimensional geometry of the regions.

### 8.6. \( L_X/L_{\text{Hα}} \) ratios versus Other Parameters

In Figures 8–10, we plot the extinction-corrected \( L_X/L_{\text{Hα}} \) ratios against the \( L_X \) equivalent widths, the hydrogen column
Smith et al.

Figure 8. Plot of the reddening-corrected $L_X/L_{H\alpha}$ ratio against $H\alpha$ equivalent width. The hinge clumps are the filled red triangles, the upside down open blue triangles are regions 3 and 4 in the Antennae, the black asterisks are other positions in the Antennae, and the open green squares are regions within NGC 2403. For this plot, the reddening correction was determined from the $L_{24}/L_{H\alpha}$ ratio as described in the text. The symbols enclosed in circles represent regions with strong X-ray point sources.

(A color version of this figure is available in the online journal.)

Figure 9. Plot of the reddening-corrected $L_X/L_{H\alpha}$ ratio against hydrogen column density, both determined using the $L_{24}/L_{H\alpha}$ ratio as described in the text. The hinge clumps are the filled red triangles, the upside down open blue triangles are regions 3 and 4 in the Antennae, the black asterisks are other positions in the Antennae, and the open green squares are regions within NGC 2403. The symbols enclosed in circles represent regions with strong X-ray point sources. (A color version of this figure is available in the online journal.)

Figure 10. Plot of the reddening-corrected $L_X/L_{H\alpha}$ ratio against electron number density $n_e \times \sqrt{f}$, where $f$ is the volume filling factor. The hinge clumps are the filled red triangles, the upside down open blue triangles are regions 3 and 4 in the Antennae, the black asterisks are other positions in the Antennae, and the open green squares are regions within NGC 2403. The symbols enclosed in circles represent regions with strong X-ray point sources; if these are ULXs, the derived $n_e$ are not relevant.

(A color version of this figure is available in the online journal.)

densities (determined from the $H\alpha/24\mu m$ ratios), and $n_e \sqrt{f}$.

We calculated $H\alpha$ equivalent widths for the Antennae regions using the Zhang et al. (2010) photometry, interpolating between the HST F555W and F814W fluxes for the red continuum. For the NGC 2403 regions, we used fluxes from the van Zee et al. (2014, in preparation) $H\alpha$ and off-$H\alpha$ images to calculate equivalent widths. These agree reasonably well with spectroscopic $H\alpha$ equivalent widths determined for a few of our NGC 2403 regions by Berg et al. (2013).

Figures 8–10 show clear differences between the NGC 2403 regions and the other regions, while the values for the Antennae and hinge clumps overlap. The NGC 2403 equivalent widths are generally larger than those for the Antennae regions and the hinge clumps. In the hinge clumps and in the Antennae regions, the ionized gas may be more obscured relative to the overall starlight, producing smaller observed equivalent widths. Lower metallicity in some of the NGC 2403 regions may also contribute to higher $H\alpha$ equivalent widths. In addition, the NGC 2403 apertures cover smaller physical areas on the galaxy, closer to the central star formation; more older stars may be included in the larger Antennae and hinge clump apertures. Since both the hinge clumps and the Antennae regions likely contain a range of stellar ages (see Appendix B), their $H\alpha$ equivalent widths are a rough proxy for the luminosity-weighted mean stellar age.

The NGC 2403 regions have lower $N_H$ and $n_e \sqrt{f}$ values than the hinge clumps and Antennae regions. This is expected, as star forming regions in normal galaxies are expected to be less obscured and less dense on average than regions in strongly interacting galaxies.

The NGC 2403 regions also have lower extinction-corrected $L_X/L_{H\alpha}$ ratios than the other regions. This may be due to younger ages on average in the NGC 2403 regions, as suggested
by their Hα equivalent widths. Very young star forming regions are not expected to host significant supernovae activity, while hot gas may build up with time in older regions with successive generations of star formation. Alternatively, the lower gas number densities and gas column densities toward the NGC 2403 regions may be responsible for their lower relative X-ray emission. The higher the density of the region, the more X-ray production is expected due to a higher particle collision rate. This topic is discussed further in the next section.

8.7. The X-Ray Production Efficiencies

To further investigate these issues, in this section we compare the large-aperture X-ray luminosities with Starburst99 predictions of the rate of mechanical energy injection into the region from hot star winds (ignoring red giant stars) and supernova. The ratio of the absorption-corrected X-ray luminosity to the mechanical luminosity is defined as the X-ray production efficiency (XPE; the fraction of the mechanical luminosity emitted in X-rays). To calculate XPEs it is necessary to have estimates of the extinction and the average stellar age. For this calculation, we use the ages and reddenings derived from the Hα data (Table 12), as these are likely more relevant for the X-ray-emitting hot gas than values obtained from the broadband photometry (Table 11). Using these values and SB99, we derive mechanical energy rates and thus XPEs for the clumps assuming that all of the X-ray light comes from hot gas and not HMXBs. These XPEs are tabulated in Table 12. Most of the hinge clumps with extended X-ray emission have similar inferred XPEs of ∼0.6%, while Arp 240-1 has a lower value of ∼0.2%

We emphasize that these XPEs are uncertain for several reasons. First, there is likely a range in both age and attenuation in these clumps, making our estimates of both the mechanical luminosity and the extinction uncertain. Second, the cooling time for the X-ray emitting gas can be quite long, while our determination of the XPE uses an instantaneous estimate of the mechanical luminosity. Ideally, in calculating XPE one should average the rate of mechanical energy injection over an extended time period, taking into account the variation of the SFR with time along with gas cooling rates. Given these caveats, it is unclear how significant the variations in XPEs are from one hinge clump to another.

However, even taking these caveats into account, two of the X-ray point sources, Arp 270-1 and Arp 240-4, have very high derived values of XPE (8.0% and 3.2%, respectively). This again suggests that these two regions host ULXs rather than hot gas, despite the possible thermal X-ray spectrum for Arp 270-1. The third X-ray point source, Arp 240-3, has an XPE similar to that of the clumps with diffuse X-ray emission, suggesting that its X-ray emission is dominated by light from hot gas.

For many of the clumps, the older ages obtained from the broadband photometry (Table 11) are inconsistent with the X-ray fluxes, if the X-ray emission is only due to hot gas, the burst is instantaneous, and the hot gas cools quickly. A dramatic drop-off in the mechanical luminosity is expected for ages older than 40 Myr, when supernovae Type II cease. However, as noted earlier, the cooling times for the hot gas can be quite long, and hot gas can build up in the regions over an extended period, thus our instantaneous estimates of XPEs may not be very accurate for these regions.

We derived XPEs for the Antennae and NGC 2403 regions in the same way as we did the hinge clumps. For the Antennae regions with $\geq 3\sigma$ detections in the X-ray, we find XPEs ranging from 0.16% to 0.91%, with a median of 0.38%, after eliminating the regions with bright X-ray point sources. These values are similar to the XPEs found for the hinge clumps. For the NGC 2403 regions, we find a lower median XPE of 0.16%. In all cases, we find a large range in the derived XPEs, perhaps reflecting the uncertainties in these estimates.

In Figures 11–14, we plot XPE against Hα equivalent width, $Spitzer$ [3.6]–[24] color, $N_\text{H}$, and $n_e\sqrt{\mathcal{J}}$. The XPE for the NGC 2207 clump is similar to or higher than that of the other hinge clumps and regions within the Antennae, in spite of its low observed $L_X/L_{24}$ ratio (see Figure 4). This suggests that its low observed $L_X/L_{24}$ ratio is primarily caused by high absorption, rather than by extremely young age. It has the highest inferred $N_\text{H}$ of the hinge clumps (see Table 12) thus the largest correction for extinction, but only a moderate Hα equivalent width.

Antennae region 3 has an XPE similar to that of NGC 2207-1 but a lower inferred column density and a higher Hα equivalent width. Thus it appears younger but less obscured. Antennae region 4 has a low inferred XPE and a high implied column density. Region 4 in the Antennae does not have an extremely high Hα equivalent width (Figure 11), despite the very young estimated age of 1 Myr for the most luminous cluster WS80 in this region (Whitmore et al. 2010). This suggests that region 4 contains a wide range of stellar ages and extinctions. The extinction of the Hα line toward the youngest stars may be significantly higher than that of the observed red stellar continuum, which would artificially bias the observed Hα equivalent width toward older ages.

The three hinge clumps that are undetected by $Chandra$ (Arp 270-2, Arp 270-3, and Arp 270-4) have XPE upper limits consistent with the X-ray detections of the other hinge clumps and the detected Antennae regions (Figures 11–13). This suggests that their lack of X-ray emission is simply due to low SFRs. They have the lowest SFRs in our sample (Table 10).

Figure 11. Plot of X-ray production efficiency $= L_X/L_{\text{mech}}$ vs. Hα equivalent width. The hinge clumps are the filled red triangles, the upside down open blue triangles are regions 3 and 4 in the Antennae, the black asterisks are other positions in the Antennae, and the open green squares are regions within NGC 2403. The symbols enclosed in circles represent regions containing strong X-ray point sources. (A color version of this figure is available in the online journal.)
Figure 12. Plot of X-ray production efficiency $= L_X / L_{\text{mech}}$ against the [3.6]–[24] color. The hinge clumps are the filled red triangles, while open blue upside down triangles are regions 3 and 4 in the Antennae, the black asterisks are other positions in the Antennae, and the open green squares are regions within NGC 2403. The symbols enclosed in circles represent regions containing strong X-ray point sources. The reddest hinge clump in [3.6]–[24] is NGC 2207; the second reddest is Arp 240-3.

(A color version of this figure is available in the online journal.)

Figure 13. Plot of X-ray production efficiency $= L_X / L_{\text{mech}}$ vs. $N_H$, where $N_H$ was calculated from the $L_{24}/L_{\text{H} \alpha}$ ratio, with the assumptions given in the text. The hinge clumps are the filled red triangles, while open blue upside down triangles are regions 3 and 4 in the Antennae, the black asterisks are other positions in the Antennae, and the open green squares are regions within NGC 2403. The symbols enclosed in circles represent regions containing strong X-ray point sources.

(A color version of this figure is available in the online journal.)

Figure 14. Plot of X-ray production efficiency $= L_X / L_{\text{mech}}$ vs. electron density $n_e \sqrt{f}$, where $f$ is the volume filling factor. The hinge clumps are the filled red triangles, while open blue upside down triangles are regions 3 and 4 in the Antennae, the black asterisks are other positions in the Antennae, and the open green squares are regions within NGC 2403. The symbols enclosed in circles and marked by lower limit symbols represent regions containing strong X-ray point sources. These may be ULXs, for which the estimate of $n_e$ is not valid.

(A color version of this figure is available in the online journal.)

with the exception of Arp 270-1, which has a candidate ULX. Arp 270 is the closest system in our sample, thus our selection criteria reach lower luminosities for clumps in Arp 270 than for the other galaxies.

A weak correlation between XPE and $H\alpha$ equivalent width is visible in Figure 11, while the XPEs do not correlate with the [3.6]–[24] colors of these clumps (Figure 12). Theoretical studies suggest that the XPE in star forming regions should increase with time (Silich et al. 2005; Añorve-Zeferino et al. 2009; Hopkins et al. 2012). The large scatter in these plots may be because there is likely a range of stellar ages and/or extinctions within a clump, thus our simple estimate of XPE using a single age and single extinction is quite uncertain. In addition, there may be contributions from HMXBs to the extended X-ray emission in these regions, which are not taken into account in our calculation of the XPE. Another factor is the timescale for cooling of the hot gas; hot gas can build up in the region over an extended period, thus the rate of mechanical energy injection into the region from the star formation should be averaged over an extended time period.

We see a weak correlation between XPE and hydrogen column density $N_H$ (Figure 13), and between XPE and $n_e \sqrt{f}$ (Figure 14), when excluding the sources that are likely ULXs. This is consistent with theoretical expectations, which suggest that XPE should increase with increasing gas density (Silich et al. 2005; Añorve-Zeferino et al. 2009; Hopkins et al. 2012). Lower density gas allows stellar winds to escape more freely, while higher density gas would incur more collisions, thus producing more X-ray emission. The large scatter in XPE with $n_e \sqrt{f}$ (Figure 14) may be due in part to the large uncertainties on both of these quantities. In addition to uncertainties in the derived stellar ages and the possibility that there is a
range of ages within the clumps, other contributing factors may be uncertainties in the measured angular extent of the X-ray emission, which is a function of sensitivity, as well as uncertainties in the line-of-sight path length through the ionized region.

9. SUMMARY AND DISCUSSION

We have investigated the properties of a visually selected sample of 12 bright hinge clumps in five interacting galaxy systems. We limited our sample to those with extensive multi-wavelength archival data available including GALEX UV, Spitzer IR, 2MASS, Hz, and SDSS imaging. Most critically, we have also examined high resolution HST images of the hinge clumps to investigate their morphology in detail and Chandra X-ray data to study their hot gas and luminous X-ray binary populations. Comparisons have been made with star forming regions in the Antennae galaxies and in the normal spiral NGC 2403. Some of these hinge clumps are forming stars at prodigious rates, between 1–9 M sun yr$^{-1}$, higher than the global values for many normal spiral galaxies, while others are more quiescent.

We find remarkably large (∼70 pc) and luminous (M$_{L}$ ∼ $-12.2$ to $-16.5$) UV/optical sources at the centers of these clumps. These sources are sometimes embedded in long arcs or linear ridges containing fainter star clusters, suggestive of star formation along a narrow caustic. The sizes of these central sources are much larger than typical super star clusters, and their luminosities are near the high luminosity end of the super star cluster luminosity function. These results suggest that they are likely composed of close concentrations of multiple star clusters, rather than individual clusters.

Comparison to stellar population synthesis models suggests that the hinge clumps contain a range of stellar ages. This is consistent with expectations based on models of interacting galaxies which predict prolonged inflow of gas into the hinge region, producing sustained star formation or multiple bursts rather than a single instantaneous burst. The central sources seen in the HST images are bluer on average than the clump as a whole, again suggesting a range of stellar ages within the clump. A jewel-in-the-crown mode of star formation may operate within hinge clumps, in which luminous young star clusters form within a “crown” of older stars, dispersed from earlier star formation episodes.

These results all indicate that hinge clumps, as a population, are relatively long-lived structures. How long hinge clumps persist and form stars is an unanswered question. Our selection criteria for this study selected targets that are bright in either UV or 24 μm light, which restricts our sample clumps to be younger than ∼200 Myr, the lifetime of the UV-producing stellar population. However, our morphological definition of hinge clumps, that they are discrete knots of recent star formation in the inner portion of a tidal feature, can include fainter and presumably older structures.

Analytical and numerical models (Struck & Smith 2012) suggest hinge clumps arise in regions of global compression formed by multiple converging density waves that produce ocular waves and caustics in the outer disks of interacting galaxies. These structures may be long lived but are more subject to shear in the relatively flat rotation curve environment of outer disks compared to nuclear starbursts that reside near the bottom of the galaxy potential. The models suggest much more intense interaction between azimuthal and radial caustic waves in the outer disk, near the base of the tails, than elsewhere in the system in the pre-merger stage of a tail-producing encounter.

Determining how long hinge clumps may last and their ultimate fate depends on the specific details of the galaxy interaction that produced them. While the dynamical explanation for hinge clump formation appears robust, current simulations lack sufficient resolution and the necessary microscale physics needed to make reliable predictions of their ultimate fate. However, if the galaxy interaction is a simple flyby, then it is likely that the larger hinge clumps will eventually spiral into the nucleus through dynamical friction while the smaller ones may disperse through shear in a few rotation periods. If the galaxy interaction results in a merger, the star clusters within hinge clumps may be dispersed intact as self-gravitating bodies and may eventually become globular clusters. It is uncertain if and how such globular clusters could be differentiated from the ordinary populations of old globular clusters.

Several of the hinge clumps studied in this work are prodigious X-ray emitters ($L_X \sim 10^{40}$–$10^{41}$ erg s$^{-1}$). In most cases, this emission appears extended and is best interpreted as originating from a hot, $\sim$0.3 keV, thermal plasma. Hot gas is expected in regions of intense star formation. Where this gas is confined by dense surrounding cooler interstellar medium, the hot gas cooling times are short and the energy input into the hot gas is quickly radiated away, giving rise to a high X-ray luminosity. In lower-density regions, in contrast, hot gas bubbles do $P dV$ work on the surroundings giving rise to galactic winds but with little radiative losses (Hopkins et al. 2012). The converging flow of gas and stellar orbits that produce hinge clumps may be sufficient to confine the hot gas produced by supernovae and stellar winds and thus produce the high X-ray luminosities and high XPEs observed in several of our sample hinge clumps, similar to those of star forming regions within the merging Antennae galaxies. In contrast, the star forming regions in the normal spiral galaxy NGC 2403 have lower XPEs, consistent with their lower inferred electron number densities and hydrogen column densities.

In three of the hinge clumps, the X-ray emission is either point-like or point-like with an underlying extended soft component (Arp 240-4). In one case (Arp 240-3), the X-ray spectrum and luminosity indicate a compact star forming region; the other two sources are likely ULXs. Arp 240-4 is the most X-ray luminous hinge clump in the sample, with a hard X-ray spectrum and an extreme X-ray luminosity of $\sim 2 \times 10^{41}$ erg s$^{-1}$. This luminosity is difficult to explain by a single HMXB; it may be a collection of HMXBs or alternatively, an intermediate mass black hole. If this source is indeed an intermediate mass black hole, its mass is 1600–16,000 M$_\odot$, assuming it is radiating at 10%–100% of the Eddington luminosity. The ratio of the mass of this black hole to the stellar mass of this clump (Tables 11 and 12) would then be $1.5 \times 10^{-4}$ to $7.5 \times 10^{-6}$. Massive clumps and clusters hosting intermediate mass black holes may eventually migrate into the center of the galaxy, where the black holes may merge into supermassive central black hole (e.g., Ebisuzaki et al. 2001; Elmegreen et al. 2008).

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APPENDIX A

MORPHOLOGIES OF INDIVIDUAL GALAXIES

A.1. Arp 82 (NGC 2535/6)

Arp 82 is an unequal mass pair with a long tail extending to the north (Figure 15, left). The more massive galaxy in the north NGC 2535 has an ocular structure (Elmegreen et al. 1991; Kaufman et al. 1997; Hancock et al. 2007). In an earlier study (Hancock et al. 2007), we conducted a detailed analysis of the GALEX/Spitzer/Hα photometry of numerous clumps of star formation in Arp 82. Luminous knots of star formation are present along the eyelids and points of the ocular (Hancock et al. 2007). In the current study, we target the most luminous knot of star formation in the tidal features, which lies near the base of the northern tail (marked in Figure 15). We classify this region as a hinge clump. This knot shows up as a discrete source in the 20 cm radio continuum image and the 21 cm Hα map of Kaufman et al. (1997).

In Figure 16, we present a close-up view of the HST F606W image of the hinge clump. In the center of this clump, we find a very luminous source with absolute I magnitude $M_I \sim -13.3$. This source is unresolved with HST (FWHM diameter $\lesssim 70$ pc). This object lies near the center of a straight line of fainter star clusters. The HST archival images of Arp 82 were included in the Mullan et al. (2011) large statistical study of the frequency of clusters in tidal features, however, their study did not present any analysis of individual clusters or cluster associations. No Chandra data is available for Arp 82.

We presented a numerical simulation of the Arp 82 interaction in Hancock et al. (2007). The model indicates that the long tail was produced in a prograde planar encounter, with the companion in an elliptical orbit around the primary. In the right panel of Figure 17, we display an analytical model of a prolonged prograde interaction (approximated by three tidal impulses) from Struck & Smith (2012, their Figure 12). We compare with a close-up view of the Arp (1966) Atlas.
photograph of the hinge region of Arp 82 (left panel). Note the resemblance between the model and the galaxy. The inner disk of the model galaxy shows an ocular structure similar to that in NGC 2535. A larger oval-shaped structure is visible in the model outside of the inner ocular. This structure is produced when two caustics diverge and one arcs back to the main galaxy. Arp 82 shows a similar morphology in the northeast, where a spiral arm loops back toward the main galaxy. Further along the model tail to the north, two caustics converge, causing a narrowing of the tail. In the Arp picture, a similar narrowing of the tail occurs at the location of the hinge clump, and a faint arc is visible extending to the west. This suggests that the star formation in the hinge region was triggered by intersecting caustics.

A.2. Arp 240 (NGC 5257/8)

Figure 18 compares the HST F435W image of Arp 240 with the Spitzer 8 μm image. Arp 240 is a pair of disk galaxies with similar masses, with a connecting bridge and two short tails extending from the two galaxies. Both galaxies in the pair are independently classified as “Luminous Infrared Galaxies” (LIRGs), with far-infrared luminosities of $2 \times 10^{11} \, L_\odot$ (Howell et al. 2010). Arp 240 has a total of five clumps that we define as hinge clumps, one in the southeastern galaxy of the pair (NGC 5258), and four in the northwestern galaxy (NGC 5257). These are marked in Figure 18. X-ray emission is detected from all five of these clumps.

Arp 240W has an inner spiral, along with two clumpy ridges of star formation to the west and east of this spiral, at the base of the tails. In the Spitzer 8 μm image of Arp 240W, three knots of star formation are seen along the base of the southern tail, and a fourth at the base of the northern tail. These four regions are all bright in the CO (3–2) map of Wilson et al. (2008) as well as in the Bushouse (1987) Hα map.

A closer view by HST of Arp 240W (Figure 19 left) shows that each of the four hinge clumps in this galaxy contains a central luminous source. The absolute B magnitudes $M_B$ of these sources range from $-14.4$ for Arp 240-4 to $-15.1$ for Arp 240-1, while $M_K$ ranges from $-14.4$ for Arp 240-4 to $-15.6$ for Arp 240-2. These clusters are resolved in the HST images, with FWHM between $\sim 40$ pc for Arp 240-2 to $\sim 100$ pc for Arp 240-3. In the HST images, the brightest optical source in clump 2 is about 2″ off from the 8 μm peak, but well within the 5″ radius used for the Spitzer photometry. For clump 3, the brightest optical source is about 1″ from the 8 μm peak. For clump 1, the source that is the brightest in the HST UV and optical images is not the brightest in the near-infrared F160W image. Both of these sources are about 3″ from the 8 μm peak.

In Figure 19 (right), we overlay a smoothed version of the Chandra 0.3–8 keV map on the HST F814W image of Arp 240W. Diffuse X-ray emission is present along the base of the tidal features; this extended emission is predominantly soft X-rays. Clump 4, at the base of the northern tail, has a bright compact source with a hard X-ray spectrum. Clump 3 is also compact in the X-ray; however, its spectrum is intrinsically soft (see Section 3.3).

In Figure 20, we compare the HST F814W image of Arp 240W with an analytical model from Struck & Smith (2012) that approximates the structure of Arp 240W (see the text for details).
Figure 21. Left: a closer view of the HST F814W image of the hinge clump in Arp 240E (clump 5). The hinge clump is marked by a 5″ radius circle. Right: The smoothed 0.3–8 keV Chandra map of Arp 240E. North is up and east to the left. Notice the strong and spatially extended X-ray emission from this source ($L_X = 1.4 \times 10^{41}$ erg s$^{-1}$ after correction for internal extinction). The HST image shows an extremely luminous source near this location ($M_I = -16.5$ with $\leq 75$ pc diameter.)

(A color version of this figure is available in the online journal.)

Figure 23. Left: a close-up view of the HST F814W image of Arp 256N. A 5″ radius encircling the hinge clump is marked. Note the flattened structure of the bright source near the center of the hinge clump. Right: the smoothed 0.3–8 keV Chandra image of the same region, plotted as contours on the F814W image.

(A color version of this figure is available in the online journal.)

and its very distorted structure, unlike Arp 240W we are not able to match it to one of our analytical models. However, the location and luminosity of the star formation region suggests it may be a hinge clump.

A.3. Arp 256

Arp 256 is a widely separated pair of spirals (Figure 22). The southern galaxy has a far-infrared luminosity of $2.8 \times 10^{11} L_\odot$, thus it is classified as a LIRG, while the northern galaxy has $L_{FIR} = 2.3 \times 10^{10} L_\odot$ (Howell et al. 2010). According to an archival 70 μm Herschel image, most of the far-infrared luminosity from the southern galaxy comes from the inner disk, while the far-infrared light from the northern galaxy is dominated by a luminous knot of star formation at the base of its long northern tail. We classify this knot as a hinge clump.

In Figure 22, we compare the HST F435W image of Arp 256 with the Spitzer 8 μm image. In addition to the hinge clump in the northern tail, the northern galaxy in Arp 256 has a tidal dwarf galaxy near the end of its southern tail. A 21 cm H I map of this system has been presented by Chen et al. (2002), which shows that these tails are gas-rich. The hinge clump is very bright in the 20 cm radio continuum (Chen et al. 2002).

In Figure 23, we display a close-up view of the HST F814W image of the hinge clump. This region is resolved in the HST red and near-infrared images into a flattened structure with an FWHM ~ 70 pc, much larger than the typical size of the super star clusters found in interacting galaxies (~3 pc; Larsen 2004). This source is extremely luminous ($M_B \sim -14.6$ and $M_J \sim -14.8$). In the HST UV image, this source resolves into two peaks separated by ~0′.15 (80 pc) north/south; this double structure may be due to dust absorption; alternatively, the slightly higher spatial resolution in the UV may be resolving a pair of clusters. As in Arp 82 and 240, this source is embedded in a linear ridge of star clusters. This ridge lies along the leading edge of the tidal tail. The X-ray emission from this region (Figure 21, right panel) is extended, with two possible peaks.

As with Arp 82, the long northern tail of Arp 256N signals a prograde planar encounter. In an earlier study, we produced a numerical simulation of the similar system Arp 305 (Hancock et al. 2009). This same simulation can be applied to Arp 256, but at an earlier timestep (see the second panel in Figure 4 in Hancock et al. 2009). A closer look at the northern tail of Arp 256N shows a double structure (Figure 24). We find an approximate match to this tidal morphology using the same analytical model as for Arp 82, but at an earlier timestep. This is illustrated in Figure 25, where we compare the HST images of Arp 256N with this analytical model (3rd panel from Figure 12 in Struck & Smith 2012). Note the two approximately parallel
caustics along the model tail. In the Arp 256 tail, the hinge clump lies near where the two main filaments in the tail intersect (see Figure 25).

In the HST images (Figure 25), two UV-bright knots of star formation are visible out of the main disk of the galaxy, above and below the bulge of the galaxies. The numerical model suggests that that star formation was triggered by material pulled out from the galaxy by the interaction, which is now falling back in on the disk. These star forming regions produce the characteristic “X” shape seen in the inner region of Arp 256 in the Arp (1966) Atlas photograph (Figure 24).

A.4. Arp 270 (NGC 3395/6)

The GALEX NUV and Spitzer 8 μm images of Arp 270 are displayed in Figure 26. Arp 270 is a close pair of equal-mass spiral galaxies with a 10′ (79 kpc) long Hα tail stretching from the eastern edge of the pair and extending to the south and west (Clemens et al. 1999). We include four tidal star forming regions in Arp 270 in our hinge clump sample. All four of these are associated with the western galaxy NGC 3395. The first three Arp 270 clumps have the lowest Hα luminosities (<10⁴⁰ erg s⁻¹) of the hinge clumps in our sample (see Table 6). Only one of the four hinge clumps in Arp 270 was detected in the X-ray, clump 1 (Figure 27, right). This source was included in our earlier survey of X-ray point sources in Arp galaxies (Smith et al. 2012). As noted in Section 3.3, this source has a soft X-ray spectrum. This source is coincident with the Spitzer mid-infrared position, which is a bit offset from the UV peak. A number of other X-ray point sources are detected in Arp 270, but none of these are associated with the other hinge clumps. Diffuse X-ray emission is seen in the inner region of the galaxy, but not in the hinge clumps.

Based on a numerical simulation, Clemens et al. (1999) conclude that the Arp 270 encounter is prograde with respect to the western galaxy NGC 3395 and retrograde with respect to the edge-on galaxy in the east, NGC 3396, and the two galaxies are on their second approach. They conclude that the long Hα tail originated from the western galaxy NGC 3395, and its apparent connection to NGC 3396 is a projection effect. In this model, the tail originates from the western side of NGC 3395 and arcs around behind NGC 3396 (Clemens 1998). In optical images (Figure 27), NGC 3395 has two tail-like structures extending to the west: the outer tail containing our target clumps, and an inner spiral. Whether the long Hα tail connects to the outer tail or the inner spiral is uncertain.

None of the analytical models in Struck & Smith (2012) resemble NGC 3395 in any detail, perhaps because of its warped and distorted structure. The closeness of the two galaxies in this pair argues that this system is in a later stage of evolution than the other systems in our sample and closer to merger, thus it is harder to model analytically. We include the four marked regions in our sample as possible hinge clumps due to their apparent location near the base of tidal features and the availability of high sensitivity Chandra data; however, whether or not their formation was triggered by intersecting caustics is uncertain. The only HST images of Arp 270 do not cover the hinge clumps (Hancock et al. 2003), thus we do not have high resolution optical images available to study the morphology of these regions in more detail.

A.5. NGC 2207

IC 2163 and NGC 2207 are two spiral galaxies with similar masses in a very close interacting pair. In Figure 28, we display the GALEX NUV and Spitzer 8 μm images of this pair. The Spitzer images of this system were previously presented by...
Elmegreen et al. (2006), who noted an extremely mid-infrared-bright knot of star formation on the western edge of NGC 2207. This source, which they call “feature i,” is our hinge clump candidate, and lies in a distorted spiral arm at the base of a short tail-like feature visible in optical images. Feature i lies near a massive concentration of H$_1$ gas ($\sim 10^8 M_\odot$); a second similar concentration ($8 \times 10^8 M_\odot$) is seen 1’ ($11$ kpc) to the north of knot i (Elmegreen et al. 1995). This second H$_1$ cloud is visible in the GALEX NUV image, and may be a gas-rich extension of the tail-like feature containing feature i. The companion galaxy IC 2163 to the east has an ocular structure (Elmegreen et al. 1990). Kaufman et al. (2012) noticed a possible increase in 6 cm flux between 1986 and 2001, and suggested a possible radio supernova.

The HST images of NGC 2207 were previously analyzed by Elmegreen et al. (2001), before the Spitzer images were obtained. In that study, they only considered the optically brightest clusters, which did not include the cluster in the center of the mid-infrared object feature i. The HST morphology of the NGC 2207 hinge clump (Figure 29) differs somewhat from that of the other hinge clumps in our sample. The dominant source in the NGC 2207 hinge clump is at the center of a more extended grouping of fainter clusters, rather than in a straight line of clusters. However, this group of clusters is part of an extended ridge of star formation along a spiral arm/short tail-like structure, thus it may also have been produced by star formation along a caustic, albeit a more distorted caustic.

The source at the center of this clump is extended in the HST images, with FWHM $\sim 70$ pc. Its observed absolute $I$ magnitude is only about $-12.2$, however, its intrinsic luminosity might be much higher if it is strongly obscured. As noted by Kaufman et al. (2012), there is a dust lane visible in optical images that runs across feature i. The extinction to this clump is discussed further in Section 7.3.

The unsmoothed X-ray map of the NGC 2207 hinge clump is shown in Figure 29 (right). This source is quite extended with Chandra but with a low surface brightness, and has a soft X-ray spectrum. The Chandra data for this source was previously analyzed by Mineo et al. (2013), who also concluded that the source is soft and extended with Chandra, and found an observed flux similar to ours.

We classify feature i as a possible hinge clump based on its location near the base of a short tail-like structure and its strong mid-infrared emission. However, this classification is uncertain because of the shortness of the tail and the peculiar morphology, which differs from that of the other systems in our sample. Feature i may instead be a tidally disturbed disk region rather than a true tidal structure.

The NGC 2207/IC 2163 encounter has been modeled numerically by Struck et al. (2005), who conclude that the collision was prograde with respect to IC 2163, and retrograde for NGC 2207. In contrast, the other hinge clumps in our sample all lie in longer tidal features produced by prograde encounters. However, the basic mechanism of star formation triggering due to intersecting caustics may still hold for feature i. Models suggest that the eastern H$_1$ tail of IC 2163 may eventually develop hinge clumps, once sufficient time has elapsed for strong waves to develop and intersect in that region.

APPENDIX B

COMPARISON TO THE ANTENNAE

B.1. Overview

To put our hinge clumps in perspective, we compare them to the well-studied “overlap” region of intense star formation between the two disks of the Antennae galaxies. Like the hinge clumps, this region is not in a galactic nucleus, thus it is easier to study and less confused than nuclear starbursts. At a distance of only 24.1 Mpc, the Antennae provides much better spatial resolution than the hinge clump galaxies, thus it provides a good comparison system. The star clusters in the Antennae have been investigated in a number of studies, including a detailed population synthesis study by Whitmore et al. (2010).

In Figure 30, we provide a multi-wavelength mosaic of the Antennae overlap region, including the co-added Chandra 0.3–0.8 keV map (upper left panel), an archival HST ACS F814W (I band) image from the Hubble Legacy Archive (upper right panel), an archival HST WF3C F160W image (near-infrared H band; middle left panel), and the Spitzer 8 $\mu$m map (middle right panel). We also compare to a 230 GHz millimeter continuum map and a CO(2–1) map, respectively, from the Atacama Large Millimeter/submillimeter Array (ALMA) telescope, previously presented by Espada et al. (2012) and obtained from the ALMA science portal$^{12}$ (lower left and lower right panels in Figure 30). On these images we superimpose circles marking two of the 45 radius regions studied by Zhang et al. (2010): their region 3 (right) and region 4 (left). Region 4 lies near the peak of the 8 $\mu$m and 24 $\mu$m emission, and has been called the mid-infrared “hot spot.” It has the reddest [3.6]–[24] color of all the Antennae regions studied by Zhang et al. (2010; see Section 5). Region 3 is also quite bright in the mid-infrared, and is the second reddest region in [3.6]–[24] in their survey. These red colors imply intense and obscured star formation in these regions.

B.2. Region 4

From the $L_{24}/L_{140}$ ratio we determine an extinction of $A_V = 3.23$ toward region 4. Probably because we are averaging over the entire region, this value is significantly less than that found

$^{12}$ http://almascience.nao.ac.jp/almadata/sciver/AntennaeBand6
by Whitmore et al. (2010) toward the brightest cluster visible in region 4 in the *HST* F814W image, for which they estimate $E(B-V)=2.44$. This cluster is also extremely massive, $8.2 \times 10^{6} M_{\odot}$, and has an extinction-corrected $M_{K}=−15.4$ (Whitmore et al. 2010). This object is sometimes called “WS80,” being object number 80 from Whitmore & Schweizer (1995) study. Whitmore et al. (2010) derive an age of only 1 Myr for this cluster. Whitmore & Zhang (2002) associate WS80 with the cluster in region 4 is known as WS80 (source 80 from Whitmore & Schweizer 1995), while the brightest complex of star clusters in region 3 is called Knot B (Rubin et al. 1970; Whitmore et al. 2010). The spatial resolution of the ALMA maps is 1.6′ × 0.85′.

(A color version of this figure is available in the online journal.)

In contrast to WS80 in region 4, the brightest cluster in Zhang et al. (2010) region 3 is closely surrounded by other bright clusters. This complex of clusters is known as “Knot B” (Rubin et al. 1970; Whitmore et al. 2010). Whitmore et al. (2010) find a range of ages for the clusters in this complex from 2.5 Myr to 50 Myr, with the youngest ages found preferentially to the east. They suggest that this may be a case of sequential triggered star formation. The clusters in Knot B are significantly less obscured than WS80 in region 4 but still quite reddened, with $E(B-V)∼0.12–1.0$ (Whitmore et al. 2010). The most massive cluster in Knot B is almost as massive as WS80, with $5.0 \times 10^{6} M_{\odot}$. This region is much fainter in CO than WS80.

Most of the diffuse X-ray emission from region 3 is located near Knot B. In addition, an X-ray point source lies approximately 3′ to the south of knot B near an optical point source. The X-ray spectrum of this source appears very absorbed, implying a very large intrinsic $L_{X}$. Its spectrum has a peak near 3 keV, and can be fit with a disk blackbody model with $kT \sim 0.75–1$ keV.

### B.3. Region 3

The large apparent sizes and the high luminosities of the objects seen in the centers of the hinge clumps by *HST* may be caused by the blending of multiple clusters very close together. We can make use of the relative proximity of the Antennae star forming regions to explore some of the results of this blending. We investigate what regions 3 and 4 would look like in the *HST* F814W image with a Gaussian to the effective aperture. Region 4 as a whole shows a composite X-ray spectrum, with both a power law and a thermal component with $kT = 0.68 ± 0.13$ keV. More than half of the power law flux arises from the point source. The point source has a pure power law spectrum with $L_{X} \sim 3 \times 10^{38}$ erg s$^{-1}$.

If the Whitmore et al. (2010) age estimate for WS80 of 1 Myr is accurate, WS80 itself is too young to host HMXBs or to have developed supernovae. The point source may be an HMXB associated with a nearby slightly older stellar population, while the diffuse X-ray emission in this region may be powered by supernovae associated with an earlier generation of stars or hot star winds rather than supernovae. The spatial offset between the X-ray, the optical, and the mid-infrared sources in region 4 suggest an age sequence from older in the southwest to younger in the northeast.

### B.4. Comparison to Our Hinge Clumps

The large apparent sizes and the high luminosities of the objects seen in the centers of the hinge clumps by *HST* may be caused by the blending of multiple clusters very close together. We can make use of the relative proximity of the Antennae star forming regions to explore some of the results of this blending. We investigate what regions 3 and 4 would look like in the *HST* images if they were at the distance of our hinge clumps. We smoothed the *HST* F814W image with a Gaussian to the effective resolution it would have if it were at a distance of 102 Mpc (the distance of Arp 240). The clusters in Knot B of region 3 become blended together into a single extended object with FWHM $\sim 110$ pc $\times 120$ pc. In region 4, the WS80 region is only marginally resolved in the smoothed image, with FWHM $\sim 80$ pc. This exercise suggests that the extended sources we are seeing in the *HST* images of the hinge clumps could be blended complexes of clusters that are very closely packed together.

We note that larger than normal clusters have also been found in the tidal features of the merger remnant NGC 3256 and Stephan’s Quintet by Trancho et al. (2007, 2012). These authors suggest that the large sizes may be a consequence of less tidal stripping of the outer stars in these clusters or weak compression at the time of formation. It is possible, however,
that the NGC 3256 and Stephan’s Quintet sources are also multiple clusters blended together, however, at 37 Mpc and 88 Mpc, respectively, they are not as distant as some of the hinge clumps in our sample. Larger than usual clusters are also seen in the merger remnant NGC 7252 (Bastian et al. 2013).

At the distance of Arp 82 (53 Mpc), Antennae regions 3 and 4 would be included in a single 5′′ Spitzer and GALEX aperture. The [3.6]−[24] color would still be quite red, although these regions contain a range of stellar ages. An area on the Antennae equivalent to that covered by our 5′′ aperture at Arp 82 would be observed to have a [3.6]−[24] color of 8.7, similar to the value for region 3 alone. If the Antennae were further away, at the distance of Arp 240, the southern nucleus would be included in a 5′′ beam along with regions 3 and 4. Thus the Antennae overlap region is not a perfect analogy to the hinge clumps, as it is closer to its nucleus than the hinge clumps are to their galactic nuclei.

In the Chandra map of the Antennae shown in Figure 30, outside of region 3 to the southeast is a ridge of diffuse X-ray emission. This ridge continues several arcseconds to the outside of region 3 to the southeast is a ridge of diffuse X-ray emission. This ridge continues several arcseconds to the southeast beyond the field of view of the figure. This ridge of emission was studied by Metz et al. (2004), who concluded that it was likely caused by faint older stars (~100 Myr). In the HST F814W and F160W images, a few faint star clusters are seen.

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