NGC 2207/IC 2163: A GRAZING ENCOUNTER WITH LARGE-SCALE SHOCKS

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1. INTRODUCTION

The spiral galaxies NGC 2207 and IC 2163, at a distance of 35 Mpc (1″ = 170 pc; Elmegreen et al. 1995b) and partially overlapping in projection, are involved in a nearly grazing encounter with closest approach 200–400 Myr ago. We have studied this pair extensively (Elmegreen et al. 1995a, 1995b, 1998, 2000, 2001, 2006; Thomasson 2004; Struck et al. 2005) throughout the electromagnetic spectrum with Hubble Space Telescope (HST) WFPC2 observations in UBVI bands, ground-based Hα, Spitzer/IRAC (3.6–8 μm), and MIPS (24–160 μm) observations, Very Large Array (VLA) H I and radio continuum, and 12CO J = 1 → 0 (Swedish ESO Submillimeter Telescope (SEST)) observations and reproduced many of the observed features with N-body and smoothed particle hydrodynamics encounter simulations. Relative to IC 2163, the encounter is prograde and nearly in-plane, producing the observed eye-shaped (ocular) oval and two long tidal arms in IC 2163. Relative to NGC 2207, the encounter is retrograde with IC 2163 moving behind NGC 2207 toward the east. The short-lived ocular phase and other features of this system set strict constraints on the numerical model for the encounter. Along the rim of the ocular oval, there is a large-scale shock front caused by the inflow of gas responding to tidal torques. This observed shock is a signature of the early stages of prograde grazing encounters. The models in Struck et al. (2005) predict that disk or halo scraping between the companion sides of the two galaxies would push shocks at ∼200 km s−1 into each other across a front 30″–60″ in length, with a mass transfer stream from IC 2163 impinging on NGC 2207. Evidence for this may be seen in the radio continuum image as enhanced radio emission from the outer part of the companion sides of NGC 2207 and IC 2163. According to the models in Struck et al. (2005), the two galaxies in this system will eventually merge.

To extend our previous studies of this galaxy pair, we observed NGC 2207/IC 2163 in X-rays and the ultraviolet with XMM-Newton and made new radio continuum observations with the VLA7 at 6 cm at a resolution of 2.5″, comparable to that of the ultraviolet and Spitzer/IRAC images. The goals of the X-ray observations were (1) to detect the predicted soft X-ray emission from diffuse hot plasma at the large-scale shock fronts produced by the grazing encounter and (2) to determine the

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ABSTRACT

Radio continuum, Spitzer infrared, optical, and XMM-Newton X-ray and ultraviolet observations (UVW1 and UVW2) are used to study large-scale shock fronts, young star complexes, and the galactic nuclei in the interacting galaxies NGC 2207/IC 2163. There are two types of large-scale shock fronts in this galaxy pair. The large-scale shock front along the rim of the ocular oval in IC 2163 has produced vigorous star formation in a dusty environment, bright in the Spitzer 8 μm and 24 μm images. In the outer part of the companion side of NGC 2207, a large-scale front attributed to halo scraping is particularly bright in the λ6 cm and λ20 cm radio continuum but not in any tracers of recent star formation (Hα, 8 μm, 24 μm, or ultraviolet emission) or in X-rays. This radio-continuum front may be from compression of the halo magnetic field on the back side of NGC 2207, between the two galaxies. The X-ray emission sets an upper limit to the gas density in the halo. Values of the flux density ratio S, (8 μm)/S, (6 cm) of prominent, kiloparsec-size, Spitzer/IRAC star-forming clumps in NGC 2207/IC 2163 are compared with those of giant radio H II regions in M81. For the bright clumps in NGC 2207, the mean value of this ratio is the same as for the M81 H II regions, whereas for the bright clumps on the rim of the IC 2163 ocular oval, the mean value is nearly a factor of two greater. Possible explanations for this are discussed. The galaxy pair has global values of the ratios of infrared-to-radio continuum flux density in the Spitzer 8 μm, 24 μm, and 70 μm bands, and the IRAS FIR significantly below the medians/means for large samples of galaxies. Feature i, a mini-starburst on an outer arm of NGC 2207 on its anti-companion side, is the most luminous 8 μm, 24 μm, 70 μm, radio continuum, and Hα source in the galaxy pair. We find evidence that a radio supernova was present in the core of feature i in 2001. X-ray emission is detected from the nucleus of NGC 2207 and from nine discrete sources whose X-ray luminosities make them possible candidates for Ultraluminous X-ray sources. One of these corresponds with the Type Ib SN 1999ec, which is also bright in the ultraviolet, and another may be a radio supernova or a background quasar. The X-ray luminosity of the NGC 2207 nucleus is log L0.3–10keV = 40.6 erg s−1, which, together with its X-ray spectrum, suggests that this is a highly absorbed, low-luminosity, active galactic nucleus.

Key words: galaxies: individual (NGC 2207/IC 2163) – galaxies: interactions – radio continuum: galaxies – supernovae: individual (SN 1999ec) – X-rays: galaxies
number, location, and nature of bright, discrete X-ray sources in this pair. The XMM-Newton observations presented here are the first deep X-ray observations of NGC 2207/IC 2163. Note that this galaxy pair was not detected in the ROSAT All-Sky Survey (Voges et al. 1999).

We use our radio continuum, Spitzer infrared, optical, and XMM-Newton X-ray, UVW1 (effective $\lambda = 2910$ Å) and UVM2 (effective $\lambda = 2310$ Å) observations to study the large-scale shock fronts, the young star complexes, the NGC 2207 nucleus, and various discrete X-ray sources in these galaxies. In an outer spiral arm on the anti-companion side of NGC 2207, there is a morphologically peculiar star-forming region (called feature i) by Elmegreen et al. 2000 which is the most luminous Hα, radio continuum, 8 $\mu$m, 24 $\mu$m, and 70 $\mu$m source in NGC 2207/IC 2163. At 24 $\mu$m, it accounts for $\sim12\%$ (Elmegreen et al. 2006) of the total emission from the galaxy pair. Feature i contains an opaque dust cone (400 pc in projected length) aligned nearly parallel to the minor axis of the projection of NGC 2207 into the sky plane. We present new results on feature i and its environs.

IC 2163 and NGC 2207 each have an SFR/M(Hi) typical of normal spiral disks, with a star formation rate (SFR) deduced from Hα emission. The radio continuum flux density of NGC 2207/IC 2163 is about three times higher than expected from the IRAS far-infrared flux (Elmegreen et al. 1995b), yet neither galaxy contains a radio-loud active galactic nucleus (AGN). The global value of the Helou $q_{\text{FIR}}$ parameter (the logarithm of the ratio of FIR to $\lambda>20$ cm radio continuum flux density) is $1.81$ for NGC 2207/IC 2163, whereas Condon (1992) finds the median value of $q_{\text{FIR}}$ for galaxies that are not radio-loud AGNs to be $\sim2.3$ with an rms scatter of $\sim0.2$. Other galaxies with a similarly low global value of the Helou $q_{\text{FIR}}$ parameter are NGC 2276 (Hummel & Beck 1995) and the Taffy pairs UGC 12914/15 and UGC 813/6 (Condon et al. 1993, 2002; Peterson et al. 2012). The Taffy pairs, NGC 2207/IC 2163 and NGC 2276, represent three different types of interactions. (1) In the Taffy pairs, the bridge between the galaxies is prominent in the radio continuum, Hα, H2, and $^{12}$CO $J = 1 \rightarrow 0$ emission. Condon et al. (1993, 2002) and Peterson et al. (2012) conclude that this results from a face-on collision between the two galaxies, and Lisenced & Volk (2010) suggest that 10%–30% of the collisional kinetic energy of the two colliding gas disks has been converted into the energy of relativistic particles in the bridge. (2) The collision between NGC 2207 and IC 2163 is a grazing collision with IC 2163 moving behind NGC 2207, not a face-on collision. (3) Like NGC 2207, the spiral galaxy NGC 2276 has enhanced radio emission in the outer part on one side of the galaxy. The lopsided appearance of NGC 2276 has been attributed either to ram pressure from hot intragroup gas (Rasmussen et al. 2006) or to a tidal interaction with the elliptical galaxy NGC 2300 (Hummel & Beck 1995; Davis et al. 1997). Rasmussen et al. (2006) observed the interacting galaxy pair NGC 2276/NGC 2300 with Chandra and found a shock-like feature in X-rays. NGC 2276 had already been observed in X-rays with the ROSAT High-Resolution Imager (Davis et al. 1997). We shall compare NGC 2207/IC 2163 with NGC 2276 and with the Taffy pairs. Explaining why the radio continuum emission from the galaxy pair is enhanced without a commensurate effect on star formation is important for understanding the conditions necessary for star formation in general.

Section 2 describes our new observations (X-ray and ultraviolet from XMM-Newton and $\lambda6$ cm radio continuum from the VLA) and the data reductions. Section 3 presents an overview of the system. Section 4 discusses star-forming clumps prominent in the Spitzer 8 $\mu$m (IRAC 4) image and/or in the XMM-Newton ultraviolet images (UVM2 and UVW1). Values of the flux density ratio $S_\text{FIR}/S_\text{UV}$ (6 cm) for these kiloparsec-size clumps are compared with those of giant HII regions in M81 as an example of what is normal for an OB association. Section 5 presents our results on the large-scale shock fronts and comments on infrared-to-radio continuum ratios. Section 6 describes our X-ray results. Section 7 compares NGC 2207/IC 2163 with NGC 2276 and with the Taffy pairs. Section 8 is devoted to feature i and its environs. Section 9 summarizes our conclusions.

For this galaxy pair, we adopt the distance of 35 Mpc as in Elmegreen et al. (1995b), who used $H_0 = 75$ kpc s$^{-1}$ Mpc$^{-1}$.

## 2. OBSERVATIONS AND DATA REDUCTION

### 2.1. XMM-Newton Observations

XMM-Newton observed NGC 2207/IC 2163 on 2005 August 31 for a total of 51.6 ks. A summary of the observations in each of the instruments on board XMM-Newton is given in Table 1. The European Photon Imaging Camera (EPIC) pn (Strüder et al. 2001) was operated in Extended Full-Frame mode and the two EPIC MOS (Turner et al. 2001) in Full-Frame mode. All observations with the EPICs were performed with the thin filters. Due to some episodes of high particle background at the beginning of the observations, part of the pn observation had to be discarded, leaving a net observing time of 34.2 ks. The MOS data, however, were not affected by this high background flux and we used the entire observations.

The XMM-Newton data were analyzed in the standard way using the XMMASAS version xmmssas_20060628_1801-7.0.0. Only single and double events (PATTERN = 1 and single to quadruple events (PATTERN = 12) were selected for the pn and MOS data, respectively. Events in or next to the CCD gaps were rejected from the analysis (FLAG = 0). For our final X-ray image, the screened event files of the pn and MOS data were merged with the XMMASAS task merge. The spectra were rebinned by grppha version 3.0.0 with 20 photons bin$^{-1}$ in the pn and 15 counts bin$^{-1}$ in the two MOS cameras. The redistribution matrices and the auxiliary response files were created by the XMMASAS tasks rmfgen and arfgen, respectively. Spectral fits to the EPIC pn and MOS spectra were performed with XSPEC version 12.5.0ac (Arnaud 1996). All errors are 90% confidence unless stated otherwise.

### Table 1

| Instrument | Mode/Filter | T-start | T-stop | $T_{exp}$ |
|------------|-------------|---------|--------|-----------|
| EPIC pn    | Ext FF      | 07:14:11| 20:36:01| 47640     |
| EPIC MOS-1 | FF          | 06:13:14| 20:25:41| 51567     |
| EPIC MOS-2 | FF          | 06:13:14| 20:36:01| 51572     |
| OM         | U           | 06:17:52| 07:37:32| 4460      |
| OM         | U           | 07:37:38| 08:57:28| 4479      |
| OM         | B           | 08:57:24| 10:23:15| 4840      |
| OM         | B           | 10:23:16| 11:43:01| 4460      |
| OM         | UVW1        | 11:43:02| 13:02:47| 4460      |
| OM         | UVW1        | 13:02:48| 14:22:23| 4460      |
| OM         | UVM2        | 14:22:34| 15:42:19| 4460      |
| OM         | UVM2        | 15:42:20| 17:02:05| 4460      |
| OM         | UVM2        | 17:02:06| 18:21:51| 4479      |

Notes:
- $^a$ Start and end times are given in UT.
- $^b$ Observing time given in seconds.
Throughout the paper spectral indices are denoted as energy spectral indices with flux density $F_{\nu} \propto \nu^{-\alpha}$. Spectral index has the same type of definition for the X-ray and for the radio observations.

For the MOS X-ray image, the FWHM of the point-spread function (PSF) is $5''$ on-axis. The $4.1$ pixel size for the pn X-ray camera results in somewhat poorer spatial resolution than for the MOS cameras ($1.1$ pixels). According to the XMM-Newton User’s Handbook, the core of the PSF for the X-ray cameras varies little over the energy range 0.1–4 keV and is somewhat triangular in shape for the MOS2 camera. The half energy width (at which 50% of the total energy is encircled) is $15''$ for the XMM-Newton X-ray images.

Comparison of the XMM-Newton X-ray, radio continuum, and Spitzer infrared positions of the NGC 2207 nucleus indicates that the positional accuracy of the X-ray data is about $3''$.

We also took advantage of XMM-Newton’s multi-wavelength capacity by using the optical monitor (OM; Mason et al. 2001) performing photometry in four filters ($B$, $U$, $UVW1$, and $UVM2$). We use the UVW1 (effective $\lambda = 2910 \text{Å}$) and UVM2 (effective $\lambda = 2310 \text{Å}$) images to study prominent star-forming clumps by comparing the ultraviolet, radio continuum, and $8 \mu\text{m}$ flux densities and H$\alpha$ fluxes. The UVM2 band, with response to the $\lambda$ range 2000–2700 Å, is somewhat similar to the GALEX NUV, which has response to the $\lambda$ range 1750–2750 Å with an effective wavelength of 2267 Å. The observing times and exposure times are listed in Table 1. The OM data were processed with the XMMSAS task omichain. During the course of the observations a $3''$ southward drift in declination occurred and the OM onboard software did not correct for it. Instead, by using foreground stars in the Guide Star Catalog or in the Two Micron All Sky Survey image or in the Spitzer/IRAC 1 (3.6 $\mu$m) image as standard stars, we applied a plate solution to the ultraviolet images to register them to the same coordinates as the Spitzer and radio continuum images. The task omichain creates for each exposure a source list containing raw and corrected counts s$^{-1}$ and magnitudes. We used the source-list data on foreground stars in the field outside of the galaxies to convert image units to counts s$^{-1}$ and magnitudes in the final stacked image and to check on corrections for dead time and sensitivity degradation.

2.2. Radio Observations at $\lambda 6\text{ cm}$

With the VLA, we observed NGC 2207/IC 2163 in the radio continuum at a central frequency of 4860.1 MHz for 92 minutes (on the target) in B configuration on 2001 April 14 and for 50 minutes (on the target) in D configuration on 1995 May 13. The observations were made with one intermediate frequency pair at 4885.1 MHz with a 50 MHz bandwidth and the other at 4835.1 MHz with a 50 MHz bandwidth. The phase center was R.A., decl. (2000) = 06 16 22.665, −21 22 06.87. For the B configuration (high-resolution) observations, the phase calibrator was 0606-223, the flux calibrators were 3C 286 and 3C 147, and the polarization calibrators were 3C 138 and 3C 286. No significant polarization was detected. For the D configuration (low-resolution) observations, the phase calibrator was 0607-157 and the flux standard was 3C 286. Our D configuration observations were not appropriate for a polarization calibration.

The AIPS software package was used for the data reduction. After calibrating the $uv$ data from each of the VLA configurations separately and checking the separate maps, we combined the $uv$ data sets from the two configurations and ran the AIPS task IMAGR with ROBUST = −2 to make and clean a map with a synthesized beam of $2''.8 \times 1'.3$ (HPBW) and BPA = 8°. After convolution to a circular beam of 2'.5 (HPBW) and correction for primary beam attenuation was a factor of 1.2. In this image, which is displayed in Figure 1, a surface brightness of 1 mJy beam$^{-1}$ corresponds to $T_b = 8.279$ K and the rms noise is 0.016 mJy beam$^{-1}$, equivalent to $T_b = 0.13$ K. We find a total flux density from the galaxy pair in this image $S_\nu (4.86 \text{ GHz}) = 0.132 \pm 0.001 \text{ Jy}$, with about $20\%$ of this from IC 2163. The single-dish observations of the Parkes–MIT–NRAO survey (Griffith et al. 1994) list $S_\nu (4.85 \text{ GHz}) = 0.10 \pm 0.01 \text{ Jy}$ for NGC 2207; it is not clear whether the latter includes IC 2163.

2.3. Additional Data

Other images of this galaxy pair that we use here are the WFC2 HST$^2$ B-band image from Elmegreen et al. (2000), the Spitzer/IRAC and MIPS images from Elmegreen et al. (2006), the H$\alpha$ image from Elmegreen et al. (2001), the VLA H$\alpha$ and line-free $\lambda 20$ cm radio continuum images from Elmegreen et al. (1995b), and a radio continuum image at 8.46 GHz ($\lambda 3.5$ cm) from the VLA public archives (Program AK 509) from 2003 January 14 observations. Table 2 lists the FWHM of the PSFs of the images we use. The VLA H$\alpha$ and radio continuum images have Gaussian synthesized beams (PSFs). The other images do not, and some of the non-radio images, such as the Spitzer $8 \mu$m and $24 \mu$m images and the XMM-Newton X-ray images, have significant side lobes.

The NASA Gamma-Ray Burst explorer mission Swift (Gehrels et al. 2004) observed the field of NGC 2207/IC 2163 as part of a monitoring campaign of SN 2010 jp (Smith et al. 2012) 12 times between 2010 November 15 and December 9 for a total of 26.2 ks (target ID 31869). The Swift X-ray Telescope (XRT; Burrows et al. 2005) operated in Photon Counting mode (Hill et al. 2004) and the UV/Optical telescope (Roming et al. 2005) obtained data in all six filters. In general, we use the Swift/XRT data only for consistency checks on the XMM-Newton X-ray images.

### Table 2

| Image       | FWHM of PSF | Reference       |
|-------------|-------------|----------------|
| HST B WFPC2 | $0''.18^a$  | Elmegreen et al. (2001) |
| UVM2        | $1''.8$     | This paper       |
| UVW1        | $2''.0$     | This paper       |
| MOS X-ray   | $5''$       | This paper       |
| MOS + PN X-ray | $9''$     | This paper       |
| Swift/XRT   | $18''$      | This paper       |
| Spitzer 8 μm | $2''.4$     | Elmegreen et al. (2006) |
| Spitzer 24 μm | $6''$      | Elmegreen et al. (2006) |
| Spitzer 70 μm | $18''$     | Elmegreen et al. (2006) |
| Spitzer 160 μm | $40''$     | Elmegreen et al. (2006) |
| $\lambda 3.5$ cm radio continuum | $11''.7 \times 3''.5$ | VLA public archives |
| $\lambda 6$ cm radio continuum | $2''.48 \times 1''.3$ | This paper       |
| $\lambda 6$ cm radio continuum | $2''.5$ | This paper       |
| $\lambda 6$ cm radio continuum | $6''$ | This paper       |
| $\lambda 20$ cm radio continuum | $13''.5 \times 12''$ | Elmegreen et al. (1995b) |
| H1          | $13''.5 \times 12''$ | Elmegreen et al. (1995b) |
| SEXT 12 CO J = 1 → 0 | $43''$ | Thomasson (2004)       |
| Hα          | $4''.2 \times 3''.6$ | Elmegreen et al. (2001) |

Note. $^a$ $0''.08$ for wide field and $0''.09$ for planetary camera.

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*Image credit: NRAO/VLA Archive Survey, (c) 2005–2007 AUI/NRAO.*
Figure 1. Top: gray scale plus contour display of the $\lambda 6$ cm radio continuum image. The rms noise is 0.016 mJy beam$^{-1}$, equivalent to $T_b = 0.13$ K, and the contours are at 4, 8, 16, 32, and 64 times the rms noise. The label i marks feature i, the long tilted box marks the location of the NE radio ridge, and the label N6, the location of massive H$\text{I}$ cloud N6. Bottom: the same contours of $\lambda 6$ cm emission overlaid on the HST $B$-band image.

pn data. However, for the X-ray source X3 and the extended X-ray emission from the NE radio ridge, we use the Swift/XRT spectrum in place of the XMM-Newton spectrum. For these two sources, the Swift/XRT data turned out have a better signal-to-noise ratio than the pn data because of the much lower detector background of Swift/XRT. Due to the low number of counts in the Swift/XRT data, we applied Cash statistics (Cash 1979) in doing spectral fits to the Swift spectra.
3. OVERVIEW OF THE SYSTEM

Figure 1 displays our $\lambda$6 cm radio continuum image and the WFPC2 HST $B$-band image of this galaxy pair, and Figure 2 displays our UVM2 image and the Spitzer 8 $\mu$m image overlaid with contours of the line-of-sight H\textsc{i} column density $N$(H\textsc{i}) associated with each galaxy. The two galaxies partially overlap in projection, with NGC 2207 in front. IC 2163 has an eye-shaped oval midway out in the disk and a tidal tail on the anti-companion side. The H\textsc{i} image of IC 2163 reveals a symmetric tidal bridge arm on the companion side; it is harder to discern in the infrared or optical because it lies behind the central disk of NGC 2207 but can be faintly traced in the HST $B$ band (see Figure 3 in Elmegreen et al. 2001) and Spitzer/IRAC images. The rim of the eye-shaped oval (which we call the eyelids) in IC 2163 is outlined by optical, radio continuum, H\textsc{i}, and infrared emission and is particularly bright in the Spitzer 8 $\mu$m and 24 $\mu$m images. The eyelids are one of the large-scale shock fronts that we investigate in Section 5. They are produced by radial streaming and convergence of orbits due to tidal forces (see the velocity vectors of the model displayed in Figure 2 of Elmegreen et al. 2000), which concentrate old stars as well as young stars in the eyelids (Elmegreen et al. 1995b). The other large-scale shock is the long ridge of enhanced radio continuum emission on the companion (eastern) side of NGC 2207; in Figure 1, a tilted box 54$^\prime\prime$ (9 kpc) long is drawn around it. We call it the NE radio ridge. Aside from the highly luminous feature $i$, the companion side of NGC 2207 is substantially brighter in the radio continuum than its anti-companion side, with the brightest large-scale radio emission coming from the NE radio ridge. The radio continuum emission from the adjacent companion side of IC 2163 is also enhanced. This is evidence of either disk or halo scraping between the two galaxies.

The NE radio ridge overlaps the optical spiral arms of NGC 2207 that are visible in the HST $B$-band image. These are not the outermost spiral arms of NGC 2207 on the companion
side. The bottom panel in Figure 2 displays an outer H\(\text{I}\) arm of NGC 2207 cutting in front of the western part of the northern eyelid of IC 2163 and the eastern part of the southern eyelid. The extinction due to this outer arm of NGC 2207, which is seen backlit by IC 2163 in the HST image (Elmegreen et al. 2000), partly explains the faintness of the western part of the northern eyelid and the eastern part of the southern eyelid in the UV2 image. This arm has values of N(H\(\text{I}\)) \(\geq 3 \times 10^{21}\) atoms cm\(^{-2}\). Assuming the outer disk of NGC 2207 is somewhat metal poor, Elmegreen et al. (2001) adopt for the relation between extinction and H\(\text{I}\) column density, \(A_\lambda = (0.35 \pm 0.18) \times 10^{-21} N(H\text{I})\). For a foreground dusk screen, the ultraviolet extinction \(A(\text{UV2}) = 2.6 A_\lambda, A(\text{UVW1}) = 2.0 A_\lambda\) (Savage \& Mathis 1979). Thus, \(A(\text{UV2})\) on this arm \(\geq 2.7 \pm 1.4\) mag. In the \(\lambda 6\) cm image in Figure 1, another outer arm of NGC 2207 is visible cutting across just north of the nucleus of IC 2163.

There is also significant gas in the eyelids of IC 2163. The top panel of Figure 2 displays the N(H\(\text{I}\)) associated with IC 2163. Using the SEST, Thomasson (2004) detected \(^{12}\text{CO} J = 1 \rightarrow 0\) emission from both disks; the brightest \(^{12}\text{CO} J = 1 \rightarrow 0\) emission is from the central part of IC 2163 and has an integrated intensity, averaged over the beam, of 6 K km s\(^{-1}\), equivalent to \(10^{21} \text{H}_2\) cm\(^{-2}\) if we use the Milky Way Conversion factor \(X_{\text{CO}} = N(\text{H}_2)/I_{\text{CO}} = 1.8 \pm 0.3 \times 10^{20}\) from Dame et al. (2001). The resolution of SEST (43' HWPW) is too low to tell if this \(^{12}\text{CO} J = 1 \rightarrow 0\) emission is mainly from the eyelids although the double-peaked nature of the \(^{12}\text{CO} J = 1 \rightarrow 0\) line profile of IC 2163 suggests this may be the case (Struck et al. 2005). Except for a bright \(^{12}\text{CO} J = 1 \rightarrow 0\) source on the northwest inner arm of NGC 2207, the SEST \(^{12}\text{CO} J = 1 \rightarrow 0\) image closely resembles the Spitzer/MIPS image at 160 \(\mu\)m of this galaxy pair (Elmegreen et al. 2006). Both have about the same resolution, and the close correspondence tells us that the cooler dust measured by the 160 \(\mu\)m emission has about the same distribution globally as the molecular gas, which is not surprising. We can infer the distribution of gas from the distributions of cooler and warmer dust, as indexed by the 70 \(\mu\)m and 24 \(\mu\)m emission, respectively. Aside from some of the structures (see the figure in Section 5.1 below and the HiRes deconvolution of the 70 \(\mu\)m and 24 \(\mu\)m images in Velusamy et al. 2008), and thus the highest concentration of gas in IC 2163 is in the eyelids.

Elmegreen et al. (1995b) identified 11 unusually massive (\(10^8\)–\(10^9\) \(M_{\odot}\)) H\(\text{I}\) clouds in NGC 2207/IC 2163. Most of these are not sites of active star formation. Clouds N1, N5, and N6 (three of the six massive H\(\text{I}\) clouds associated with NGC 2207) are labeled in Figure 2. The center of H\(\text{I}\) Cloud N6 is at R.A., decl. (2000) = 06 16 25.560, -21 22 19.08. The brightest \(\lambda 6\) cm radio continuum source on the NE radio ridge and the prominent Spitzer infrared cliff IR 12 (see Section 4) are 3' west, 1' south of the center of H\(\text{I}\) cloud N6; SN 2003H is 2" east, 5" south of the center of H\(\text{I}\) Cloud N6. H\(\text{I}\) cloud N5 obscures the ultraviolet emission from the eastern part of the southern eyelid of IC 2163. At the center of Cloud N5, N(H\(\text{I}\)) = \(4.8 \times 10^{21}\) atoms cm\(^{-2}\), which corresponds to an (A(UV2)) of 4.4 \pm 2.2 mag. Elmegreen et al. (1993) discuss the formation of massive H\(\text{I}\) clouds and tidal dwarf galaxies by large-scale gravitational instabilities in the gas and suggest that H\(\text{I}\) Cloud N1 in the outer part of NGC 2207, where large z motions are creating a warp may be in the process of forming a tidal dwarf galaxy. The only stellar emission detected from Cloud N1 forms a bow-shaped arc in the northwestern part of the cloud visible, for example, in the Digitized Sky Survey image, in the blue-band plate in Elmegreen et al. (1995b), and in the UV2 image in Figures 2 and 3. It appears that star formation has commenced in only this part of Cloud N1.

4. STAR-FORMING CLUMPS

Figure 3 displays the UV2 image overlaid with Spitzer \(8\) \(\mu\)m contours and with H\(\alpha\) contours, respectively. Aside from the effects of extinction, this demonstrates the generally good correspondence between these three tracers of recent star formation. We use photometry in \(\lambda 6\) cm radio continuum, \(8\) \(\mu\)m, UV2, UVW1, and H\(\alpha\) bands to study star-forming clumps in this galaxy pair at a resolution of \(2''\), 0.3–0.4 kpc.

Elmegreen et al. (2006) did photometry in the Spitzer/IRAC bands of 225 bright clumps in this galaxy pair by using phot in IRAF with an aperture radius of \(3'' = 0.61\) kpc, and a local background annulus with inner radius = \(9''\) and outer radius = \(15''\) concentric with the source aperture. The clumps are star complexes. In general, the source aperture includes collections of OB associations and older star clusters (see examples in Elmegreen et al. 2006). After registering the \(8\) \(\mu\)m and ultraviolet images to the same coordinate grid as the high-resolution \(\lambda 6\) cm image, we chose 28 prominent clumps in the \(8\) \(\mu\)m and/or UV2 images; these are labeled in Figure 4, which displays the \(8\) \(\mu\)m emission. For each clump, Table 3 lists the \(8\) \(\mu\)m flux density from Elmegreen et al. (2006), the H\(\alpha\) flux from Elmegreen et al. (2001), and the \(\lambda 6\) cm flux density, UV2 magnitude, and UV2 − UVW1 color measured with the same choice of source aperture and local background annulus as for the IRAC measurements. The uncertainty in the \(\lambda 6\) cm flux density of each clump is 0.04–0.05 mJy. In addition to free−free radio emission from the H\(\text{I}\) regions, the source aperture is likely to include non-thermal radio emission from the spiral arms, some of which is removed by the local background subtraction. For UV2 and UVW1, we took from the XMM-Newton User’s Handbook the zero points for the magnitudes (defined such that Vega = 0.025 mag) and the conversion factors to get from the count rates to flux densities in mJy. The conversion factors are for white dwarfs and thus the values of the UV2 flux density used in Table 3 for the ratio of \(8\) \(\mu\)m to UV2 flux density are rough estimates.

The numbering of the clumps is the same as in Elmegreen et al. (2006) except for the added clumps u1 at R.A., decl. (2000) = 06 16 20.298, -21 22 26.47 and r1 at R.A., decl. (2000) = 06 16 17.996, -21 22 04.16. In Section 6, we find that clumps IR 11, IR 21, and r1 coincide with discrete X-ray sources. The first 11 clumps in Table 3 are in IC 2163; the rest are in NGC 2207.

The values of \(A_\lambda\) in Table 3 for the NGC 2207/IC 2163 clumps are upper limits obtained from the \(\lambda 6\) cm flux density and H\(\alpha\) flux for case B recombination with \(T_e = 10^4\) K by assuming all of the \(\lambda 6\) cm flux density after subtracting the local background to be optically thin free−free emission. For a number of the clumps, the \(A_\lambda\) upper limits are quite large; this leads us to suspect that some clumps include significant non-thermal radio emission at \(\lambda 6\) cm. Within a given clump, the extinction is far from uniform as the HST observations found lots of dust features on very small spatial scales near star clusters, whose blue colors indicate little extinction (Elmegreen et al. 2001).

As an example of what is expected for the flux density ratio \(S_\lambda(8\ \mu\text{m})/S_\lambda(6\ \text{cm})\) of an OB association, we present data in...
Table 4 on the giant H ii regions in M81. We chose the 11 giant radio H ii regions in M81 which have the highest signal to noise in the \( \lambda 6 \) cm radio continuum observations of Kaufman et al. (1987) and a radio spectral index \( \alpha \) consistent with optically thin free–free emission. For these M81 H ii regions, Table 4 uses the \( \lambda 6 \) cm radio continuum flux densities from Kaufman et al. (1987) and the Spitzer \( 8 \) \( \mu \)m, \( 24 \) \( \mu \)m, and GALEX NUV flux densities from Pérez-González et al. (2006) and finds the mean value of the ratio \( S_{\nu}(8 \, \mu m)/S_{\nu}(6 \, cm) = 19 \) with the standard deviation \( \sigma \) of the sample = 5, and the mean value of the ratio \( S_{\nu}(24 \, \mu m)/S_{\nu}(6 \, cm) = 36 \) with \( \sigma = 9 \). (The average measurement uncertainties are \( \pm 3 \) and \( \pm 5 \), respectively). Comparison of these ratios with global values for entire galaxies is given in Section 5.3. The M81 H ii regions have relatively low extinction. Two estimates of the extinction \( A_{\nu} \) are listed for each H ii region: \( A_{\nu}(K) \) from Kaufman et al. (1987) is derived from \( S_{\nu}(6 \, cm)/S(\text{H}\alpha) \); \( A_{\nu}(PG) \) from Pérez-González et al. (2006) is obtained from the line ratios \( \text{H}\alpha/\text{H}\beta \) and \( \text{H}\alpha/\text{Pa}\alpha \). Except for one H ii region, these two methods give the same values for \( A_{\nu} \) within the uncertainties of the radio data.

The \( 8 \, \mu m \) emission from star-forming regions is generally attributed to young massive stars exciting aromatic hydrocarbon (polycyclic aromatic hydrocarbon, PAH) emission bands or heating very small grains. Far ultraviolet emission from B stars as well as O stars can produce significant PAH emission via fluorescence (Peeters et al. 2004). Emission at \( 8 \, \mu m \) depends on mechanisms involved in the formation and destruction of PAH molecules as well as the local SFR (Calzetti et al. 2005; Pérez-González et al. 2006; Dale et al. 2007).

From IRAC color–color plots, Elmegreen et al. (2006) find that the \( 8 \, \mu m \) emission of most of the IRAC clumps in NGC 2207/IC 2163 is PAH dominated.
Figure 4. Spitzer $8\,\mu m$ image with numbers from Table 2 labeling the measured clumps. The $3\arcsec$ radius of each circle is the aperture radius.

Table 3

| Clump | $S_r$(6 cm) (mJy) | $S_8$(8 $\mu$m) (mJy) | $S_8$/($S_r$6 cm) | $S$(H$\alpha$) (mag) | $A_v$ | $UVM2$ | ($S_8$/UVM2) | $UVM2$ − UVW1 (mag) |
|-------|-----------------|-----------------|-----------------|-----------------|-----|-------|-------------|-----------------|
| IR 1  | 0.51            | 10.4            | 21              | 0.59            | 6.1 | 18.6  | 370        | 0.49            |
| IR 2  | 0.36            | 11.9            | 33              | 0.24            | 6.9 | >19.2 | >710       | >0.00           |
| IR 3  | 0.63            | 13.5            | 21              | 0.69            | 6.2 | 19.0  | 650        | 0.58            |
| IR 4  | 0.39            | 12.5            | 32              | 2.6             | 3.7 | 17.7  | 190        | 0.38            |
| IR 5  | 0.11            | 8.2             | 72              | 4.4             | 1.2 | 16.9  | 62         | 0.10            |
| IR 8  | 0.22            | 10.3            | 47              | 0.82            | 4.4 | 16.6  | 59         | 0.06            |
| IR 9  | 0.75            | 19.3            | 26              | 2.4             | 4.7 | 16.7  | 120        | 0.17            |
| IR 10 | 0.34            | 15.0            | 44              | 1.5             | 4.3 | 17.4  | 170        | 0.24            |
| IR 11 | 0.46            | 11.2            | 25              | 2.0             | 4.3 | 18.0  | 220        | 0.13            |
| IR 81 | 0.41            | 9.6             | 23              | 1.9             | 4.1 | 18.4  | 280        | −0.23           |
| IR 6  | 0.10            | 5.5             | 57              | ...             | ... | >19.2 | >330       | >0.59           |
| IR 13 | 0.34            | 5.0             | 15              | 1.7             | 4.1 | 16.8  | 34         | 0.03            |
| IR 14 | 0.42            | 6.9             | 17              | 2.7             | 3.7 | 16.7  | 42         | 0.10            |
| IR 15 | 0.41            | 4.7             | 11              | 0.88            | 5.2 | 17.4  | 56         | 0.06            |
| IR 16 | 0.65            | 9.4             | 14              | 2.9             | 4.2 | 17.3  | 100        | 0.21            |
| IR 17 | 0.56            | 6.2             | 11              | 3.9             | 3.6 | 16.9  | 43         | 0.01            |
| IR 18 | 0.50            | 9.8             | 20              | 3.4             | 3.6 | 17.3  | 100        | 0.21            |
| IR 19 | 0.53            | 11.5            | 21              | 4.7             | 3.3 | 16.4  | 53         | −0.01           |
| IR 12f| 0.81            | 6.1             | 7.3             | 1.1             | 5.9 | 17.8  | 100        | 0.35            |
| IR 20f| 4.39            | 35.1            | 8.0             | 11.6            | 4.9 | 16.8  | 240        | 0.23            |
| IR 21b| 0.28            | 5.3             | 19              | 1.9             | 3.6 | 16.3  | 22         | −0.09           |
| IR 26 | 0.27            | 5.7             | 21              | 2.1             | 3.5 | 16.5  | 28         | −0.07           |
| IR 30 | 0.25            | 5.9             | 24              | 1.8             | 3.5 | 17.8  | 95         | 0.14            |
| IR 32 | 0.23            | 4.8             | 21              | ...             | ... | >19.2 | >290       | >0.14           |
| IR 114| 0.34            | 5.7             | 17              | 3.2             | 3.2 | 17.0  | 43         | −0.01           |
| u1   | 0.13            | 5.6             | 42              | ...             | ... | 16.2  | 22         | −0.03           |
| IR 138| <0.04           | 0.81            | ...             | ...             | ... | 17.0  | 6.2        | −0.25           |
| rc1  | 0.90            | 1.4             | 1.6             | ...             | ... | 16.8  | 8.9        | −0.10           |

Notes.

a Clumps are identified in Figure 4. IR clump positions are listed in Elmegreen et al. (2006).
b ($8\,\mu$m/6 cm) is the flux density ratio $S_8$/($S_r$6 cm).
c $S$(H$\alpha$) in units of $10^{-14}$ erg cm$^{-2}$ s$^{-1}$.
d These are upper limits obtained by assuming the radio continuum emission has no non-thermal component.
e ($8\,\mu$m/UVM2) is the flux density ratio $S_8$/($S_r$UVM2).
f In H$\alpha$ massive cloud N6 on the NE radio ridge of NGC 2207.
g Feature i.
h Contains SN 1999ec.
The mean value of the ratio $S_\nu(8\mu m)/S_\nu(6\text{ cm})$ for the 15 prominent star-forming clumps in NGC 2207 is 18 with standard deviation $\sigma = 8$. Within the uncertainties, this mean value is the same as that for the giant radio $H\alpha$ regions in M81. We excluded the clump rc1 since it is probably either a radio supernova or a background quasar (see discussion below and in Section 6). In contrast, the mean value of this ratio for the 10 prominent clumps on the IC 2163 eyelids is 34 with $\sigma = 16$. The clumps IR 5, IR 8, and IR 10 on the eyelids and IR 6 on the inner spiral arm of IC 2163 have values of $S_\nu(8\mu m)/S_\nu(6\text{ cm}) \geq 40$. The clumps on the eyelids are more luminous at $8\mu m$ but have the same mean $S_\nu(6\text{ cm})$ as the clumps in NGC 2207 (aside from feature i). As the 10 eyelid clumps are detected in $H\alpha$, they contain OB associations, but they may in addition contain somewhat older stars with ages up to several tens of million years that were collected by the occular compression front, and thus could be dominated at $8\mu m$ by PAH excitation involving B stars rather than O stars. We discuss this further in Section 5.1.

Although the source aperture used in Table 3 to measure the clumps is much greater in linear diameter (1.2 kpc versus 300 pc) than for the measurements of the M81 giant $H\alpha$ regions and thus may include emission, such as non-thermal radio emission from the spiral arm, unrelated to the OB associations, a number of clumps in NGC 2207/IC 2163 have a value of the $8\mu m$ to $\lambda 6\text{ cm}$ flux density ratio similar to those of the M81 giant $H\alpha$ regions. Either subtraction of the local background has sufficiently removed the emission unrelated to the OB associations, or these are examples at $8\mu m$ analogous to the usual FIR–radio continuum correlation for galaxies (see Section 5.3).

The three brightest discrete $\lambda 6\text{ cm}$ sources in NGC 2207/IC 2163 are the clumps IR 20 (which is feature i), rc1, and IR 12 in massive H I cloud N6. All three have low values of the $8\mu m$ to $\lambda 6\text{ cm}$ flux density ratio compared to the M81 giant $H\alpha$ regions. Non-thermal radio emission is significant in these three sources. Feature i is the most luminous radio continuum source and contains the most luminous $H\alpha$ region in the galaxy pair. VLA snapshots at $\lambda 6\text{ cm}$ and $\lambda 20\text{ cm}$ by Vila et al. (1990) indicate that feature i is dominated by non-thermal radio emission, with a radio spectral index $\alpha$ (where $S_\nu \propto \nu^{-\alpha}$) ranging from 0.7 in its 1" radio core to 0.9 averaged over a $7\times 7\prime\prime$ box. Clump rc1, the second-brightest discrete radio continuum source in Figure 1, is unresolved in that image. Clump rc1 is reasonably bright in UVM2 but does not appear as a significant clump in $H\alpha$. The faintness in $H\alpha$ is not the result of extinction, since rc1 is also rather faint at $8\mu m$. Thus, rc1 is a non-thermal radio source. It may be a supernova remnant (SNR), a radio supernova, or a background quasar. Because we detect rc1 as an X-ray source, we defer further discussion of it to Section 6. Clump IR 12 lies in the region of brightest non-thermal radio emission on the NE radio ridge.

Table 3 also lists the flux density ratio $S_\nu(8\mu m)/S_\nu(\text{UVM2})$, which is sensitive to the amount of extinction, to the distribution of extinction, to age, and to star formation history. For the star-forming clumps that are bright in the ultraviolet, low values of this ratio indicate relatively low extinction. Very high values of this ratio may indicate lots of dust and considerable absorption. From the values of the $S_\nu(8\mu m)/S_\nu(\text{UVM2})$ ratio, it appears that clumps IR 12, IR 26, u1, and IR 138 have relatively low extinction (e.g., values of $A_\nu$ similar to the M81 $H\alpha$ regions in Table 4), and that most of the clumps on the eyelids and feature i suffer high extinction. The four brightest clumps in UVM2 are u1, IR 21, IR 19, and IR 26. Relative to the $H\alpha$ and radio continuum emission, the ultraviolet emission from u1 is displaced toward the outer edge of the arm. IR 138 is a bright UVM2 clump that is faint in $H\alpha$ and $8\mu m$ emission and not detected at $\lambda 6\text{ cm}$. On the HST image, it coincides with a short, thin string of sources in the NW interarm of NGC 2207. Clumps u1 and IR 138 are probably slightly older star complexes with little dust and with ultraviolet emission mainly from B stars rather than O stars. SN 1999ec at R.A., decl. (2000) = 06 16 16.18, $-$21 22 10.1 (Van Dyk et al. 2003) is 1.2 E. 03 S of the center of IR 21. IR 21 could be bright in the ultraviolet due to shock excitation of circumstellar gas by SN 1999ec (see

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**Table 4**

| $H\alpha$ Region* | $S_\nu(6\text{ cm})$ (mJy) | $(8\mu m/6\text{ cm})^b$ | $(24\mu m/6\text{ cm})^c$ | $(8\mu m/$NUV$)^d$ | $A_\nu$(PG) (mag) | $A_\nu$(K) (mag) |
|------------------|------------------|------------------|------------------|------------------|----------------|----------------|
| K181             | 1.10 ± 0.07      | 18 ± 1           | 52 ± 3           | 12               | 0.70           | 0.5 ± 0.2      |
| K178             | 1.01 ± 0.07      | 15 ± 1           | 29 ± 2           | 31               | 1.33           | 1.2 ± 0.2      |
| K123             | 0.87 ± 0.12      | 13 ± 2           | 25 ± 3           | 21               | 0.87           | 1.0 ± 0.3      |
| K152             | 0.80 ± 0.14      | 15 ± 3           | 34 ± 6           | 15               | 0.42           | 0.6 ± 0.3      |
| K125             | 0.74 ± 0.14      | 16 ± 3           | 30 ± 6           | 15               | 0.43           | 0.5 ± 0.3      |
| K159             | 0.69 ± 0.13      | 19 ± 4           | 42 ± 8           | 17               | 1.01           | 1.0 ± 0.3      |
| K138             | 0.60 ± 0.09      | 19 ± 3           | 48 ± 7           | 12               | 0.67           | 0.7 ± 0.3      |
| K172             | 0.52 ± 0.07      | 20 ± 3           | 35 ± 5           | 9.0              | 0.73           | −0.1 ± 0.3     |
| K156             | 0.50 ± 0.10      | 21 ± 4           | 25 ± 5           | 48               | 1.91           | 2.1 ± 0.4      |
| K187             | 0.45 ± 0.08      | 29 ± 5           | 38 ± 7           | 29               | 0.36           | 0.2 ± 0.3      |
| K102             | 0.27 ± 0.05      | 28 ± 5           | 41 ± 8           | 23               | 0.88           | 0.9 ± 0.3      |
| mean             | 19 ± 5           | 36 ± 9           | 21 ± 11          | 0.85 ± 0.46      | 0.8 ± 0.6      |

**Notes.**

* The radio continuum data and $A_\nu$(K) from Kaufman et al. (1987) and the Spitzer data, GALEX NUV data, and $A_\nu$(PG) from Pérez-González et al. (2006).

* $(8\mu m/6\text{ cm})$ is the flux density ratio $S_\nu(8\mu m)/S_\nu(6\text{ cm})$.

* $(24\mu m/6\text{ cm})$ is the flux density ratio $S_\nu(24\mu m)/S_\nu(6\text{ cm})$.

* $(8\mu m/$NUV$)$ is the flux density ratio $S_\nu(8\mu m)/S_\nu($NUV$)$.

* The uncertainty listed with the mean is the standard deviation $\sigma$ of the sample, not the measurement uncertainty or the standard deviation of the mean.
comments about the corresponding X-ray source in Section 8). IR 21 resembles IR 19 and IR 26 in being fairly bright in Hα, particularly prominent in UVM2, and in having values for the 8 μm to λ6 cm flux density ratio in the same range as the M81 giant radio H II regions. A simple interpretation is that these three clumps are OB associations with less extinction than most of the other clumps and that the Hα, and most of the λ6 cm emission from IR 21 is from the H II region, not from the Type Ib SN 1999ec.

For 11 of the clumps, the value of the 8 μm to UVM2 flux density ratio is greater than or equal to 120. These include feature i, 8 of the 10 clumps on the eyelids, and the one clump on the inner spiral of IC 2163. It is not surprising to find that feature i and the eyelid clumps suffer high extinction. HST observations (Elmegreen et al. 2006) reveal a large opaque dust cloud occulting part of feature i. The eyelids contain a large concentration of gas; this is in addition to the extinction from the outer arm of NGC 2207 cutting in front.

5. LARGE-SCALE SHOCK FRONTS

We consider the two large-scale shock fronts in this system, i.e., the eyelids of the eye-shaped oval in IC 2163 and the NE radio ridge in NGC 2207. Figure 5 shows the difference between the two shock fronts. The top panel in this figure displays the ratio of the 8 μm surface brightness $I_{8 \mu m}$ to the λ6 cm radio continuum surface brightness $I_{\nu}$, and the bottom panel, the ratio of the 24 μm surface brightness $I_{24 \mu m}$ to λ6 cm radio continuum surface brightness. To match the resolution of the 24 μm image, we made a λ6 cm radio continuum image with a synthesized beam of 6″ from the λ6 cm radio observations described in Section 2.2.
location in the galaxy pair. The radio continuum emission from NGC 2207/IC 2163 is strongly non-thermal with a spectral index $\alpha = 0.92$ (where $S_\nu \propto \nu^{-\alpha}$; Condon 1983), and thus non-thermal radio emission makes a smaller contribution at $\lambda 3.5$ cm than at $\lambda 2.0$ cm. At $\lambda 3.5$ cm, the NE radio ridge is a bit brighter than the eyelids.

5.1. The Eyelids

The eyelids are particularly bright in the $8 \mu$m and $24 \mu$m images (Elmegreen et al. 2006) and also prominent in the radio and the radio continuum (see Figures 3 and 1, respectively). Aside from feature i, the brightest $70 \mu$m and $24 \mu$m emission in this galaxy pair is from the eyelids (see Figure 6), and thus cooler dust and warmer dust are both strongly concentrated on the eyelids. The eyelid shock front has produced strongly enhanced star formation in a dusty environment. Emission from warm, very small grains at $24 \mu$m is considered a better tracer than $8 \mu$m emission of the SFR (Pérez-González et al. 2006; Wu et al. 2005; Calzetti et al. 2005; Dale et al. 2007). From Figure 5 and Section 4, one sees that the ratio $S_\nu(8 \mu$m)/$S_\nu(6 \mu$m) in the eyelid is a factor of $\sim 2$ times the ratio in the NGC 2207 H ii regions, even though the $6 \mu$m flux densities are about the same, and also a factor of $\sim 2$ times the ratio in M81 H ii regions. Similarly, along the northern eyelid the values of the ratio $I_\nu(24 \mu$m)/$I_\nu(6 \mu$m) are greater than typical of the spiral arms of NGC 2207, but the effect at both eyelids is more significant at $8 \mu$m than at $24 \mu$m.

The bright $8 \mu$m emission from the eyelids is almost entirely diffuse emission, not stellar photospheric emission. We checked this by using Palhe’s method (Palhe et al. 2004) to remove the stellar contribution by scaling the surface brightness of the IRAC 1 (3.6 $\mu$m) image.

We consider three reasons for why the PAH flux in the eyelids might be twice as high as normal. All three assume that the eyelid is a large-scale compression front resulting from the tidal interaction. Such a front would have shock speeds of several tens of km s$^{-1}$ and last for at least several tens of Myr, accumulating matter into a dense ridge.

The first reason is that increased collisions between dust grains at the eyelid shock could have fragmented large grains and increased the number of small grains appropriate for emitting at $8 \mu$m and $24 \mu$m (A. Witt 2005, private communication). Jones et al. (1996) suggested that at shock speeds of $\sim 50$ km s$^{-1}$, $5\%$ of the grain mass can get shattered down to sizes below $14 \AA$, producing PAHs and tiny grains that radiate in the near-infrared. According to Draine et al. (2007), PAH particles with sizes $\lesssim 10^3$ C atoms produce most of the emission in the 7.7 $\mu$m and 8.6 $\mu$m bands.

A second explanation for the enhanced $S_\nu(8 \mu$m)/$S_\nu(6 \mu$m) concerns the accumulation of young stars as the eyelid grows in mass. The PAH emission is excited by U-band radiation, which comes from B-type stars going back for several generations, and from O- and B-type stars of the current generation. The 6 cm emission, however, like the H$\alpha$ emission, is proportional to the ionizing radiation by the OB stars in the current generation; it should have relatively little contribution from the older B stars. Thus, if previous generations of young stars are accumulating in the front, there will be an excess of B stars compared to O stars in the present-day mass function, and therefore an excess of PAH exciting radiation compared to 6 cm exciting radiation.

We can calculate the total U-band luminosity from a past history of star formation in the eyelid using population synthesis models in Bruzual & Charlot (2003). What we need to explain the observations is a U-band luminosity from old B stars.

Figure 6. Top: contours of radio continuum emission at $\lambda 20$ cm (with $13.5 \times 12''$ resolution) overlaid on the Spitzer 70 $\mu$m image (with $18''$ resolution). Contour levels at 1, 2, 3, 4, 6, 8, and 10 times 10 K. Middle: contours of 70 $\mu$m emission overlaid on the Spitzer 24 $\mu$m image. The contour levels are at 20, 30, 40, 60, 80, 100, 120, and 140 mJy sr$^{-1}$. Bottom: radio continuum emission at $\lambda 3.5$ cm (with $11.7 \times 3.5''$ resolution). The eyelids are brighter than the NE radio ridge at 24 $\mu$m and 70 $\mu$m, whereas the NE radio ridge is clearly brighter than the eyelids in the radio continuum at $\lambda 20$ cm. In this $\lambda 3.5$ cm image from observations in 2003, rc1 is much brighter than every source in the galaxy pair except feature i.

Two pixels in feature i were hard saturated and thus blanked in the 24 $\mu$m basic calibrated data. For these two pixels, we substituted twice the 24 $\mu$m surface brightness at the FWHM of the PSF. The donut-shaped appearance of feature i and its environs in the $I_\nu(24 \mu$m)/$I_\nu(6 \mu$m) ratio image (lower panel of Figure 5) results because the radio images have been cleaned of side lobes (the diffraction patterns), but the Spitzer images have not.

The differences between the two large-scale shock fronts are also apparent from the comparison in Figure 6 between the Spitzer 24 $\mu$m and 70 $\mu$m emission, and the radio continuum emission at $\lambda 20$ cm and $\lambda 3.5$ cm. The eyelids are brighter than the NE radio ridge at 24 $\mu$m and 70 $\mu$m, whereas the NE radio ridge is appreciably brighter than the eyelids at $\lambda 20$ cm. The value of the ratio of FIR to $\lambda 20$ cm emission varies with
in the eyelid that is comparable to the \( U \)-band luminosity from the young O and B stars in the current generation. The population synthesis models suggest that for times \( t > 10 \) Myr, the \( U \)-band luminosity of a single population scales as \( L_U = L_{U,10}(t/t_0)^{-1.09} \), where \( L_{U,10} \) is the luminosity after \( t_0 = 10 \) Myr. If we consider the luminosity in the eyelid \( \text{H} \text{II} \) regions today as \( L_{U,10} \), and we also consider a previous SFR in the same region equal to \( R \) of today’s regions per unit 10 Myr (that is, a new mass every 10 Myr equal to \( R \) times the present young stellar mass), then we need the integral \( R \int_{t_0}^{t} (t/t_0)^{-1.09} \) to equal about unity. That would give a sum of the \( U \)-band luminosities from previous generations of stars formed in the same region, i.e., previous to 10 Myr, that is equal to the \( U \)-band luminosity of today’s 10 Myr stars. This integral is \( 11Rt_0(1 - [t_0/\alpha])^{0.69} \). If star formation was at a steady rate in the eyelid, then \( Rt_0 = 1 \) and the integral equals unity for \( t_0/t \sim 0.3 \). That is, a steady SFR in the eyelid that began \( \sim 40 \) Myr ago would produce a total \( U \)-band flux that is twice that of a 10 Myr old population, without producing much additional ionization. This would approximately double the \( S_{\text{H} \alpha}(8 \mu \text{m})/S_{\text{H} \alpha}(6 \text{cm}) \) ratio, as required for the eyelid \( \text{H} \text{II} \) regions. What is unusual about the eyelid in this interpretation is that the old B stars are still present near the young \( \text{H} \text{II} \) regions. Presumably, this is the result of the growing accumulation of material at the ocular front (unlike a spiral wave, which passes older stars through it).

A third possibility is that shock-heated \( H_2 \) may contribute to the \( 8 \mu \text{m} \) flux density of the eyelids. IR spectra are needed to test this suggestion. An example that may be relevant to the IC 2163 eyelids is the 3C 326 radio galaxy system. Ogle et al. (2007) detect strong infrared \( H_2 \) emission from 3C 326N, which they attribute to shock-heated \( H_2 \) in a tidal accretion flow induced by interaction with its companion. If 3C 326 were at the redshift of IC 2163, then in the observed Spitzer \( 8 \mu \text{m} \) band its ratio of shock-heated \( H_2 \) emission to PAH emission would be 0.69 ± 0.36. Similarly in the Tafigy galaxies, shock-heated \( H_2 \) at the collision interface increases the \( H_2/\text{PAH} \) ratio to 0.1 for PAH in the \( 8 \mu \text{m} \) band (Peterson et al. 2012). Thus if shock heating of \( H_2 \) in the IC 2163 eyelids were strong, this could give a good part of the increase in the \( 8 \mu \text{m} \) emission that we need.

Detailed models of SEDs in starbursts by Dopita et al. (2005) consider the ratio of IR-to-radio continuum. They show that as interstellar pressure increases from \( 10^4 k_B \) to \( 10^6 k_B \), the \( 60 \mu \text{m} \) emission and the centimeter-wavelength emission both increase and their ratio is about constant. However, the \( 8 \mu \text{m} \) emission from PAHs stays about the same along this sequence, so lower pressure corresponds to increased \( S_{\lambda}(8 \mu \text{m})/S_{\lambda}(6 \text{cm}) \). For the values of \( S_{\lambda}(8 \mu \text{m})/S_{\lambda}(6 \text{cm}) \) in Table 5, the pressure in Figure 12 of Dopita et al. (2005) is already fairly low, \( \sim 10^2 k_B \). We would expect higher pressures in the eyelid. Also, the excess \( S_{\lambda}(8 \mu \text{m})/S_{\lambda}(6 \text{cm}) \) in our observations seems to arise from an excess of \( 8 \mu \text{m} \) rather than a deficit of \( 6 \text{cm} \), because the eyelid clumps have about the same \( 6 \text{cm} \) flux density as the clumps in NGC 2206, where the \( S_{\lambda}(8 \mu \text{m})/S_{\lambda}(6 \text{cm}) \) ratio is more normal (compared to M81).

We conclude that the factor of two excess in \( S_{\lambda}(8 \mu \text{m})/S_{\lambda}(6 \text{cm}) \) for the eyelids may be the result of several processes that enhance the \( 8 \mu \text{m} \) emission without a proportional change in the \( 6 \text{cm} \) emission. These include grain fragmentation in a large-scale shock front, accumulation of B stars in the eyelid, and line emission from shock-heated \( H_2 \). Explanations following Dopita et al. (2005) that do not involve the eyelid shock specifically but apply more generally to starburst regions in galaxy disks are not as favorable.

### 5.2. NE Radio Ridge

Aside from feature i, the brightest large-scale radio continuum emission in this galaxy pair comes from the NE radio ridge. In H\( \alpha \), UVM2, \( 8 \mu \text{m} \), or \( 24 \mu \text{m} \) emission, the NE radio ridge is no brighter than other spiral arms of NGC 2207. Figure 5 shows that the values of the ratio of \( 8 \mu \text{m} \) to \( \lambda 6 \text{ cm} \) surface brightness and, particularly, the ratio of \( 24 \mu \text{m} \) to \( \lambda 6 \text{ cm} \) surface brightness are low on the NE radio ridge compared to those of the M81 \( \text{H} \text{II} \) regions. The \( \lambda 6 \text{ cm} \) radio continuum emission is enhanced here without a commensurate effect on star formation. The magnetic field \( B \) is compressed, increasing the synchrotron radio emission, but some condition for enhanced star formation is not fulfilled. In IC 2163, as well as NGC 2207, the companion side is brighter than the anti-companion side in the \( \lambda 6 \text{ cm} \) radio continuum. This is evidence of disk or halo scraping between the two galaxies.

The lower panel in Figure 1 compares the \( \lambda 6 \text{ cm} \) radio continuum image with the HST \( B \)-band image. South of H\( \alpha \) massive cloud N6, the NE radio ridge includes two spiral arms of NGC 2207 visible in the \( B \)-band image, one of which is backlit by IC 2163, and some emission from IC 2163. North of cloud N6, the inside edge of the NE radio ridge coincides with an optical spiral arm, but the \( \lambda 6 \text{ cm} \) radio emission spreads significantly beyond the outer edge of this arm into the interarm and is brighter in the interarm.

A question is whether the NE radio ridge is located in the thin disk of NGC 2207 or in a thick disk or in the halo on the back side of NGC 2207 (relative to us) between the two galaxies.

If the NE radio ridge lies in the disk of NGC 2207, then it makes sense to discuss the ridge contrast (defined as the ridge-to-interarm radio disk at the inside edge of the ridge). At the 2′5 (425 pc) resolution of our high-resolution \( \lambda 6 \text{ cm} \) radio continuum image, the shock width is somewhat resolved; going to higher resolution would probably not increase the ridge contrast by a significant factor. Along the inside edge of the NE radio ridge, the interarm radio disk is detected at a level of about 2 times the rms noise in this image. Along much of this radio ridge from P.A. = 102° clockwise to 32°, the ridge contrast in surface brightness is greater than 4 and reaches a maximum of 10 at H\( \alpha \) massive cloud N6. If equipartition or minimum energy or pressure equilibrium of cosmic-ray electrons and magnetic \( B \) field applies (see, for example, Beck et al. 1985), then the intensity of radio synchrotron emission \( I_s \propto B^{3+\alpha}(nt) \), where \( \alpha(nt) \) is the non-thermal radio spectral index. The galaxy pair has \( \alpha = 0.92 \). If the free–free component of the \( \lambda 20 \text{ cm} \) radio continuum emission is \( \leq 10\% \), then \( \alpha(nt) = 0.92–1.1 \) and a ridge contrast in surface brightness of 4–10 corresponds to a factor of 1.4–1.8 increase in the magnetic field. We conclude that if the NE radio ridge is in the disk, it is a broad ridge of somewhat compressed magnetic field.

If the NE radio ridge is high off the midplane, then taking the measured ratio of the radio surface brightness on the NE radio ridge to that of the interarm thin disk at its inside edge does not make sense. The following comparison between the distributions of \( \lambda 6 \text{ cm} \) radio continuum emission, neutral gas, and cool dust in this system provides information relevant to the question of whether the NE radio ridge is in the disk. In NGC 2207, the distribution of \( 70 \mu \text{m} \) emission (see Figure 6) and the distributions of \( 160 \mu \text{m} \) emission (Elmegreen et al. 2006) and \( ^{12}\text{CO} \ J = 1 \rightarrow 0 \) emission measured at SEST (Thomasson 2004) generally correspond with the spiral arms. This indicates that molecular gas and the cool dust are cool fluids in the thin disk. The \( \text{H} \text{I} \) observations by Elmegreen et al.
(1995b) of this galaxy pair (see also Figure 2) find that along the northern side of NGC 2207, the H I ridge consistently coincides with the spiral arm, but on the eastern and western sides of NGC 2207, the H I ridge line often lies in the interarm region, the massive H I clouds are usually in the interarm, and the H I gas has high-velocity dispersion. The high-velocity dispersion leads Kaufman et al. (1997) and Elmegreen et al. (2000) to suggest that the H I gas disk may be a few times thicker than normal. The H I disk may be flared on the companion and anti-companion sides of NGC 2207 to form a thick disk. In Figure 1, we see that the bright λ6 cm radio continuum emission from NGC 2207 generally coincides well with the stellar arms except on the NE radio ridge. The most luminous radio continuum source on the NE radio ridge is in the massive H I cloud N6; cloud N6 and this radio continuum source may be in the thick disk. Along the NE radio ridge from cloud N6 clockwise to position angle P.A. = 30°, the brightest λ6 cm radio continuum emission is in the interarm. The H I emission here is also bright in the interarm. The λ6 cm emission and the H I emission on the NE radio ridge appear clumpy. However, except for cloud N6, the clumps are not in one-to-one correspondence. More importantly, unlike the radio continuum, the H I emission from the NE radio ridge is no brighter than from the opposite side of NGC 2207. This may be understood if a substantial fraction of the radio continuum emission on the NE radio ridge originates in the halo.

On scales greater than about 2 kpc in normal spiral galaxies, Adler et al. (1991) find that the ratio of 12CO $J = 1 \rightarrow 0$ intensity to radio continuum surface brightness is fairly constant. In NGC 2207, the 70 µm, 160 µm, and 12CO $J = 1 \rightarrow 0$ emission tend to be brighter on the eastern side of NGC 2207 than on its western side (aside from feature 1). However, the difference between the two sides of NGC 2207 is less pronounced for the molecular gas and cool dust than for the radio continuum. Sensitive 12CO $J = 1 \rightarrow 0$ mapping with higher spatial resolution than SEST would be useful here.

On the NE radio ridge, we may be seeing a combination in which the bright radio continuum emission at the spiral arm is from the thin disk, some of the bright radio emission is from compressed magnetic fields in a thick disk (e.g., cloud N6), but most of the interarm radio emission is from the halo on the back side of NGC 2207 (relative to us) between the two galaxies. If the compressed magnetic field is in the halo and there is little neutral gas in the halo, then it is easy to understand why the NE radio ridge is not a site of extended vigorous star formation. If the compressed magnetic field is in the thin disk, it seems necessary to invoke a time delay between compression of the magnetic field and compression of the neutral gas, which then leads to active star formation. We note that at the spiral arm, compression due to disk scraping would add to the already existing compression of the spiral density wave to produce brighter radio continuum emission.

The lack of enhanced star formation on the NE radio ridge is analogous to the lack of active star formation in most of the massive H I clouds in this galaxy pair. Much of the H I in the thick disk may be at too low a volume density and thus there is a delay before molecular clouds form.

### 5.3. Comments about IR-to-Radio Continuum Ratios

From Appleton et al. (2004), we adopt the notation $q_{IR} = \log(S_{IR}/S_{1.4GHz})$, where $S_{IR}$ is the flux density in the Spitzer $8 \mu$m, $24 \mu$m, or $70 \mu$m bands or in the IRAS FIR band, and $S_{1.4GHz}$ is the radio continuum flux density at 1.4 GHz. Note that most of the 1.4 GHz emission from whole galaxies is non-thermal, while a large fraction of the $6 \cm$ emission from H II regions discussed in previous sections is free–free emission.

In Table 5, we compare the global values of $q_{IR}$ for NGC 2207/IC 2163 with the median or mean values for galaxies in the Spitzer First-Look Survey from Appleton et al. (2004), for a sample of 30 or 35 star-forming galaxies in the Spitzer First-Look Survey from Wu et al. (2005), for IRAS galaxies that do not contain a radio-loud AGN from Condon (1992), and for galaxies in the SINGS sample, where we used the data from Dale et al. (2007). For the SINGS sample, we omitted the galaxies with poor-quality data that were excluded by Drake et al. (2007), and to have a more suitable comparison with NGC 2207/IC 2163, we also omitted the nine low-metallicity galaxies listed by Drake et al. (2007). Including the E and S0 galaxies in the SINGS sample has little effect on the mean values of $q_{IR}$ (see Table 5). For NGC 2207/IC 2163, we used the 1.4 GHz radio continuum flux density of 393 ± 9 mJy from the NRAO/VLA Sky Survey and the Spitzer $24 \mu$m and $70 \mu$m flux densities from Elmegreen et al. (2006) but revised the $8 \mu$m value to include the aperture correction for extended emission and an improved global background subtraction. The values of $q_{IR}$, $q_{70}$, and $q_{8}$ for NGC 2207/IC 2163 are consistently below the medians or means of the above large samples of galaxies by 0.4–0.6 (2σ to

### Table 5

| Samplea | $q_{IR}$ | $q_{70}$ | $q_{24}$ | $q_{8}$ | $(24 \mu m/8 \mu m)b$ |
|---------|----------|----------|----------|---------|------------------------|
| NGC 2207/IC 2163 | 1.81 | 1.79 | 0.71 | 0.49 | 1.6 |
| Spitzer First-Look | | | | | |
| Appleton et al. (2004) | ... | 2.15 ± 0.16 | ... | 0.94 ± 0.23 | ... |
| Wu et al. (2005) | ... | 1.07 ± 0.17 | ... | 0.91 ± 0.13 | ... |
| SINGSa | 2.39 ± 0.28 | 1.31 ± 0.31 | 1.12 ± 0.26 | 1.7 ± 1.6 |
| SINGSa | 2.40 ± 0.29 | 1.33 ± 0.31 | 1.15 ± 0.24 | 1.5 ± 1.1 |
| IRAS (Condon 1992) | 2.3 ± 0.2 | ... | ... | ... |
| M81 H II regions | ... | 1.50 ± 0.10 | 1.22 ± 0.12 | 1.9 ± 0.5 |

**Notes.**

a The Spitzer First-Look, SINGS, and IRAS samples refer to the integrated emission from the entire galaxy. The M81 H II region sample refers to the H II regions in Table 4. The uncertainties listed are the standard deviations σ of the samples.

b $(24 \mu m/8 \mu m)$ is the flux density ratio $S_{(24 \mu m)}/S_{(8 \mu m)}$.

c Excluding galaxies with poor-quality data or low metallicity.

d Excluding galaxies with poor-quality data or low metallicity and also omitting E and S0 galaxies.

9 From http://spider.ipac.caltech.edu/staff/jarrett/irac/
3σ, where σ is the standard deviation of the sample). The value of \( q_{24} \) for NGC 2207/IC 2163 is below the means for large samples of galaxies by 0.2–0.6, which is 2σ for the samples in Wu et al. (2005) or SINGS, but only 1σ for the sample in Appleton et al. (2004).

These values of \( q_{24} \) are for entire galaxies. Table 5 also lists the mean values of \( q_{24} \) and \( q_{6} \) for the set of M81 H\( ^{\text{ii}} \) regions in Table 4 obtained by using \( S_{\nu} \) values from Kaufman et al. (1987). The radio continuum from the M81 H\( ^{\text{ii}} \) regions is optically thin free–free emission, whereas the radio continuum of galaxies as a whole is dominated by non-thermal emission. If the galaxies as a whole have a radio spectral index \( \alpha \) of 0.8 and the H\( ^{\text{ii}} \) regions have a spectral index of 0.1, then to obtain a \( \log S_{\nu} \) value of 9 times 0.1 \( S_{\nu} \) from the MOS camera with data from the pn camera and smoothing the image to get greater sensitivity. The same screening criteria as for the X-ray spectra (see Section 2) were applied. The bottom panel shows the 8 \( \mu \)m Spitzer image with contours of X-ray emission from the MOS camera data only and with the source extraction boxes for the X-ray spectral analysis overlaid. The X-ray image used in the bottom panel has better spatial resolution (FWHM of the PSF ~ 5′) than the X-ray image in the top panel but lower sensitivity. For the discrete X-ray sources, we subtracted the local background by collecting background counts from a nearby region with the same area as the source box. With the MOS cameras, the entire field of interest fits onto a single CCD chip. With the pn camera, part of the southern eyelid of IC 2163 and parts of the discrete sources X2 and X7 in NGC 2207 fell in a gap between two CCDs.

### 6. X-RAY RESULTS

The top panel in Figure 7 displays an \textit{XMM-Newton} X-ray image in the 0.5–10 keV range obtained by combining data from the MOS camera with data from the pn camera and smoothing the image to get greater sensitivity. The same screening criteria as for the X-ray spectra (see Section 2) were applied. The bottom panel shows the 8 \( \mu \)m Spitzer image with contours of X-ray emission from the MOS camera data only and with the source extraction boxes for the X-ray spectral analysis overlaid. The X-ray image used in the bottom panel has better spatial resolution (FWHM of the PSF ~ 5′) than the X-ray image in the top panel but lower sensitivity. For the discrete X-ray sources, we subtracted the local background by collecting background counts from a nearby region with the same area as the source box. With the MOS cameras, the entire field of interest fits onto a single CCD chip. With the pn camera, part of the southern eyelid of IC 2163 and parts of the discrete sources X2 and X7 in NGC 2207 fell in a gap between two CCDs.

The X-ray images in Figure 7 clearly show the nucleus of NGC 2207 and nine other discrete X-ray sources labeled in the figure, as well as extended X-ray emission. No X-rays are detected at the position of the nucleus of IC 2163. There is little activity in the IC 2163 nucleus; it is faint (or very faint) in the radio continuum, ultraviolet, X-rays, 8 \( \mu \)m, and 24 \( \mu \)m images. The nucleus of NGC 2207 is prominent in soft X-rays, hard X-rays, radio continuum, H\( \alpha \), UVW1, and 8 \( \mu \)m images, but rather faint in the UVM2 image (as a result of extinction). The NGC 2207 nucleus is the only source in this galaxy pair that is bright in hard X-rays with \( E > 5 \) keV.

#### 6.1. Extended X-Ray Emission from NGC 2207/IC 2163

Extended X-ray emission, which may be from hot galactic gas, is mainly concentrated in NGC 2207. The encounter models for this galaxy pair (Struck et al. 2005) predicted soft X-ray emission from diffuse hot plasma at the large-scale shock fronts. One goal of our \textit{XMM-Newton} observations was to detect such emission. We find that neither the large-scale shock front along

| Region                   | \( S_{\nu}(6\text{ cm}) \) (mJy) | \( S_{\nu}(24\mu\text{m}) \) (mJy) | \( S_{\nu}(8\mu\text{m}) \) (mJy) | \( S_{\nu}/(6\text{ cm}) \) | \( S_{\nu}/(24\mu\text{m}) \) | \( S_{\nu}/(8\mu\text{m}) \) |
|-------------------------|-------------------------------|---------------------------------|-------------------------------|---------------------------|---------------------------|---------------------------|
| NE radio ridge box      | 13.2 ± 0.2                    | 121                             | 112                           | 9.1                       | 8.5                       | 0.9                       |
| Eyelid box              | 21.7 ± 0.3                    | 409                             | 506                           | 19                        | 23                        | 1.2                       |
| Combined galaxies       | 132 ± 1                       | 1.22 \times 10^3               | 2.00 \times 10^3              | 9.3                       | 15                        | 1.6                       |
| M81 H\( ^{\text{ii}} \) regions | ...                        | ...                             | ...                           | 19 ± 5                    | 36 ± 9                    | 1.9                       |

**Notes.**

- \( S_{\nu} \) (8 \( \mu \)m/6 cm) is the flux density ratio \( S_{\nu}(8\mu\text{m})/S_{\nu}(6\text{ cm}) \).
- \( S_{\nu} \) (24 \( \mu \)m/6 cm) is the flux density ratio \( S_{\nu}(24\mu\text{m})/S_{\nu}(6\text{ cm}) \).
- \( S_{\nu} \) (24 \( \mu \)m/8 \( \mu \)m) is the flux density ratio \( S_{\nu}(24\mu\text{m})/S_{\nu}(8\mu\text{m}) \).
- Uncertain because the 14″ width of the NE radio ridge box is only 2.3 \times the FWHM of the 24 \( \mu \)m PSF.
the eyelids nor the NE radio ridge appears enhanced in extended X-ray emission relative to the rest of this galaxy pair. X-ray absorption due to the large concentration of gas in the eyelids plus gas in the outer arm of NGC 2207 cutting in front of IC 2163 may explain why we do not detect significant, extended, soft X-ray emission from the eyelids. Part of the southern eyelid lies in the gap between two CCDs of the pn camera, but this is also where we find very high extinction in the ultraviolet for the star-forming clumps (Section 4). Extinction does not account for the absence of enhanced X-ray emission from the NE radio ridge as the NE radio ridge generally does not have high extinction.

In the models of Struck et al. (2005), the NE radio ridge is attributed to disk or halo scraping at a relative speed of \( \sim 200 \text{ km s}^{-1} \). The post-shock sound speed \( a = \sqrt{(5/16)}v = 112 \text{ km s}^{-1} \), and thus the shock would heat the gas to a plasma temperature \( T = 1.5 \times 10^6 \text{ K} \), suitable for emitting soft X-rays. With this value for the shock speed \( v \), we use the observed X-ray flux of the NE radio ridge to obtain an upper limit to the halo X-ray emission measure \( n^2L \), where \( n \) is the halo gas density and \( L \) is the line-of-sight path length through the shocked gas in the halo.

We use the 2010 Swift/XRT data to measure the X-ray flux of the extended X-ray emission from the NE radio ridge. Its spectrum is displayed as the bottom right-hand panel in Figure 8. With the foreground absorption column density fixed at the Galactic value from Dickey & Lockman (1990), an absorbed power-law model gives an energy spectral index \( \alpha_X = 1.26 \pm 0.60 \), an absorption-corrected flux \( F_{0.3-10.0} = (7.3 \pm 1.6) \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \) (with little emission above 2 keV), and C-statistic per dof = 22/23 (where dof = degrees of freedom). The NE radio ridge is not unusual either in terms of...
Figure 8. X-ray spectra of sources labeled in Figure 7 and listed in Table 7. The spectra were fitted with an absorbed power-law model with Galactic and intrinsic absorption as listed in Table 7. From top to bottom, the spectra in the left column are for sources X1, X4, X8, and X10 and the spectra in the right column are for sources X3, X6, X9, and the NE radio ridge. The ordinate on each spectrum is the normalized counts s$^{-1}$ keV$^{-1}$ and the plot below each spectrum is the ratio of observed-to-model counts.
its X-ray brightness or its X-ray spectrum. If the NE radio ridge were twice as bright in X-rays as other extended emission from NGC 2207, this would have been noticeable in the XMM-Newton X-ray image. Also, the X-ray spectrum of the NE radio ridge suggests that the emission could be mainly from a collection of X-ray binaries. We take as an upper limit to the halo X-ray flux from the NE radio ridge $F_{0,3-10} = 3.6 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$.

To calculate a corresponding upper limit to the emission measure from shocked gas in the halo of NGC 2207, we integrate the X-ray cooling curve in Raymond & Smith (1977) over the range 0.3–2 keV for $T = 1.5 \times 10^6$ K and get a volume emissivity $\epsilon = 1.23 \times 10^{-24}$ erg s$^{-1}$ cm$^{-3}$ $(n_T^2/4\pi)$. The flux is then $1.23 \times 10^{-22} n_T^2/4\pi \Omega$ erg s$^{-1}$ cm$^{-3}$, where the solid angle $\Omega$ subtended by the NE radio ridge is $1.83 \times 10^{-5}$ sr. Equating this to the above upper limit of the halo contribution to $F_{0,3-10}$ from the NE radio ridge gives an emission measure $n^2 L \leq 6.5$ cm$^{-6}$ pc. If the path length $L$ through the shocked gas in the halo is 1–5 kpc, then the shocked gas density $n \leq 0.081-0.036$ cm$^{-3}$, respectively. This is not an unreasonable gas density for a galaxy halo, but it may be low for the shocked part of a halo. However, the above calculation assumed that the post-shock temperature was given by the orbit speed. This temperature is probably comparable to halo gas temperature before the shock, which also comes from the depth of the galaxy potential well. In that case, the Mach number of the halo shock will be of order unity and the compression will not be large. The primary effect could be a compressed magnetic field and associated cosmic-ray acceleration, which produces the enhanced radio continuum, with a low level of X-ray from hot gas that is not bright enough to see here.

The observation that the X-ray emission from the NE radio ridge is not enhanced relative to the rest of the galaxy pair supports the suggestion that most of the bright radio continuum emission here arises in a region of much lower density than the thin disk. There is no evidence that a shock due to halo scraping has heated large quantities of gas to X-ray temperatures.

### 6.2. Discrete X-Ray Sources in NGC 2207/IC 2163

Like the extended X-ray emission, the discrete X-ray sources are mainly concentrated in NGC 2207. Aside from the NGC 2207 nucleus, most of the discrete X-ray sources lie on the spiral arms. Only a few of these correspond to the prominent IR or UV clumps discussed in Section 4.

The X-ray spectrum of each discrete source in Figure 7 plus the NE radio ridge (denoted RR in Table 7) were fitted by an absorbed power-law model with the absorption column density by the Milky Way fixed to the Galactic value fromDicke & Lockman (1990) and the absorption column density of the absorber at the location of NGC 2207 ($z = 0.00941$) left as a free parameter. The results of these fits are summarized in Table 7. The EPIC pn X-ray spectra of sources X1, X4, X6, X8, X9, and X10, and the Swift/XRT spectra of source X3 and the NE radio ridge are displayed in Figure 8. The MOS spectra of sources X2 and X7, which lie at the chip edge in the pn observations, are displayed in Figure 9. The pn and MOS spectra of X5 (the nucleus of NGC 2207) are displayed in Figure 10. Most of these X-ray spectra can be fitted with a power law with an energy spectral index of about $\alpha_X = 1.0$ (equivalent to a photon index $\Gamma$ of 2.0); source X2 has a significantly steeper index, and X5, has a more complicated spectrum. For source X3 and the NE radio ridge, we considered the Swift/XRT data to be more reliable than the XMM pn data because of the lower detector background of Swift. For the other sources with more than 10 counts in the 2010 Swift data, the results with Swift were usually consistent, with the results from XMM, given the uncertainties.

### Table 7

| Source | R.A.-2000$^b$ | Decl.-2000$^c$ | $N_{H\text{, gal}}^d$ | $\alpha_X^e$ | $\chi^2$/doF | $F_{0,3-10}^f$ | $N(HI)^g$ |
|--------|--------------|---------------|---------------------|------------|-------------|--------------|-----------|
| X1     | 06 16 17.94  | −21 22 04.5  | 0.12$^{+0.21}_{-0.12}$ | 1.05$^{+0.47}_{-0.59}$ | 20/19       | 4.70         | 0.32 ± 0.05 |
| X2     | 06 16 15.86  | −21 22 08.5  | 0.00                | 2.17$^{+1.62}_{-0.56}$ | 10/6        | 5.40         | 0.32 ± 0.08 |
| X3     | 06 16 18.83  | −21 22 30.5  | ...                | 1.07$^{+0.82}_{-0.72}$ | 27/20       | 8.10         | 0.28 ± 0.05 |
| X4     | 06 16 20.34  | −21 22 16.5  | 0.12$^{+0.21}_{-0.12}$ | 0.93$^{+0.49}_{-0.50}$ | 16/17       | 4.03         | 0.12 ± 0.03 |
| X5$^i$ | 06 16 21.89  | −21 22 25.5  | ...                | ...        | ...         | ...         | 0.14 ± 0.04 |
| X6     | 06 16 15.84  | −21 22 34.6  | 0.15$^{+0.15}_{-0.13}$ | 0.97$^{+0.46}_{-0.30}$ | 11/10       | 8.82         | 0.23 ± 0.11 |
| X7     | 06 16 17.29  | −21 22 53.2  | 0.27$^{+0.42}_{-0.24}$ | 0.86$^{+0.58}_{-0.41}$ | 20/13       | 10.4         | 0.27 ± 0.10 |
| X8     | 06 16 23.47  | −21 22 18.5  | 0.03$^{+0.12}_{-0.03}$ | 1.15$^{+0.51}_{-0.13}$ | 20/17       | 4.30         | 0.27 ± 0.10 |
| X9     | 06 16 24.95  | −21 22 28.9  | 0.04$^{+0.15}_{-0.04}$ | 1.05$^{+0.63}_{-0.43}$ | 15/17       | 3.44         | 0.41 ± 0.06 |
| X10    | 06 16 26.50  | −21 22 13.4  | 0.35$^{+0.27}_{-0.15}$ | 1.03$^{+0.40}_{-0.27}$ | 18/24       | 9.80         | 0.44 ± 0.08 |
| RR$^j$ | 06 16 25.13  | −21 22 23.4  | ...                | 1.26$^{+0.60}_{-0.59}$ | 22/23       | 7.3          | ...       |

**Notes.**

$^a$ The EPIC pn data were used for sources X1, X4, X6, X8, X9, and X10. For sources X2 and X7, only the MOS data were used. For X5 (NGC 2207 nucleus), the pn plus MOS data were fitted simultaneously in XSPEC (as shown in Figure 10).

$^b$ R.A. in h m s.

$^c$ Decl. in °, ′, and ″.

$^d$ Intrinsic absorption column density at the location of NGC 2207/IC 2163 ($z = 0.00941$) in units of $10^{21}$ cm$^{-2}$.

$^e$ Energy spectral index $\alpha_X$ for a single, absorbed, power-law model.

$^f$ Flux in $0.3–10.0$ keV band corrected for Galactic and intrinsic absorption, in units of $10^{-14}$ erg s$^{-1}$ cm$^{-2}$.

$^g$ $NH$ of the galaxy pair in units of $10^{20}$ atom cm$^{-2}$ from the 21 cm line data of Elmegreen et al. (1995b).

$^h$ Due to the small number of counts, Cash statistics were applied (Cash 1979).

$^i$ X5 = nucleus of NGC 2207. The simple absorbed power-law model does not represent the data. More complicated spectral models are listed in Table 8.

$^j$ RR is the NE radio ridge, not a discrete source.
Figure 9. X-ray MOS spectra of sources X2 (left panel) and X7 (right panel). These lie at the chip edge in the EPIC pn observations.

Figure 10. EPIC pn (black) and MOS 1 and 2 (red and green) spectra of the nucleus of NGC 2207 fitted by a power-law model with partial-covering absorber (upper left panel) and blackbody plus absorbed power-law spectrum (upper right panel). Note the hard X-ray emission at 5–10 keV. Both fits include absorption by neutral gas in the Milky Way with an absorption column density of $1.13 \times 10^{21}$ cm$^{-2}$ (Dickey & Lockman 1990). The lower left panel displays the contour plot for the absorption column density and covering fraction of the partial-covering absorber model. The lower right panel shows the blackbody component and the power-law component separately for the model in the upper right panel.

If the 10 discrete sources in Table 7 are at the distance of IC 2163/NGC 2207 and emitting isotropically, then each has an X-ray luminosity $L_x \geq 5 \times 10^{39}$ erg s$^{-1}$. Thus, each of the nine discrete sources in the disks of this galaxy pair is a ultraluminous X-ray source (ULX) candidate. Since each could be a collection of sources, e.g., X-ray binaries, rather than a single object, Chandra high-resolution observations and re-observing to look for variability are necessary.
to check on this. From Chandra data on 32 nearby galaxies, Colbert et al. (2004) find that most of the discrete X-ray sources in the disks of spiral galaxies have spectra that fit an absorbed power law with $\Gamma \approx 1$–2, appropriate for high-mass X-ray binaries associated with accretion-powered black holes, low-mass X-ray binaries, and ULXs, and that only the Antennae merger pair (NGC 4038/39) contains more than three ULXs. From a study of ULXs in 82 galaxies, Swartz et al. (2004) conclude that 14% of ULX candidates in spiral galaxies are probably background sources. Only the following four galaxies in their sample have more than five ULXs: M82, M51, NGC 4038, and NGC 4486. From Chandra observations of the interacting starburst pair NGC 7714/7715, Smith et al. (2005) identify 11 candidate ULXs, only two of which are more luminous than the faintest discrete X-ray source listed in Table 7 for NGC 2207/IC 2163. If most of the candidates in NGC 2207 are ULXs that would be a greater number than in a typical galaxy.

Note that Chandra observed NGC 2207/IC2163 on 2010 July 18 for a total of 13 ks. While most sources listed in Table 7 appear to be point sources, sources X2 and X8 appear to be diffuse and source X10 clearly consists of at least two sources.

For comparison with the intrinsic absorption column densities $N_{\text{H,intr}}$ obtained by fitting the X-ray continuum, Table 7 lists the column density $N(\text{H})$ of the galaxy pair as measured in the 21 cm line VLA observations (Elmegreen et al. 1995b), averaged over the X-ray extraction aperture and not corrected for helium. In addition to $N(\text{H})$, there is a significant H$_2$ column density in much of this galaxy pair (Thomasson 2004). The discrete sources, X2, X8, and X9 have no significant intrinsic absorption along the line of sight, which places them in the layers of the NGC 2207 gas disk closest to the observer. Source X1 may lie close to the midplane of the NGC 2207 gas disk. Most of the other discrete sources are more deeply embedded or located toward the farther side of the NGC 2207 gas disk.

We have the following identifications or possible identifications of the discrete X-ray sources (see Figure 4 for the labeling of the 8 $\mu$m or ultraviolet clumps): X5 is the nucleus of NGC 2207, X10 is in the star-forming clump IR 11 on the eyelid of IC 2163, X1 coincides with clump rc1, and X2 corresponds with clump IR 21, which contains SN 1999ec. The value of $N_{\text{H,intr}}$ for source X10 is consistent with its location in clump IR 11 on the eyelid of IC 2163 behind an outer arm of NGC 2207; the H$_2$ column density of NGC 2207 at X10 is $0.32 \times 10^{22}$ atom cm$^{-2}$ and thus the fitted value of $N_{\text{H,intr}}$ places X10 behind NGC 2207 but on the nearer side (relative to us) of the gas layer in the eyelids. The coincidence between X10 and star-forming clump IR 11 suggests that X10 contains a high-mass X-ray binary. Alternatively, Smith et al. (2005) note that some discrete X-ray sources in star-forming regions may be due to SNRs with high-mass progenitors, rather than high-mass X-ray binaries. Source X5 (the nucleus of NGC 2207) is the brightest X-ray source in the entire field. As a matter of fact it is the only X-ray source in the hard X-ray band above 5 keV. We shall discuss sources X5 and X1 in Sections 6.3 and 6.4, respectively, and source X2 in Section 8.

6.3. The Nucleus of NGC 2207

Figure 10 displays the pn and MOS spectra of the nucleus of NGC 2207 and shows that its emission contains a hard X-ray component. In order to increase the signal-to-noise ratio, all three spectra were fitted simultaneously in XSPEC. For all fits, the absorption column density of the Milky Way was fixed to $1.3 \times 10^{21}$ cm$^{-2}$ (Dickey & Lockman 1990).

\begin{table}[h]
\centering
\caption{X-Ray Spectral Fits to the NGC 2207 Nucleus (X5)\textsuperscript{a}}
\begin{tabular}{lccccc}
\hline
XSPEC Model & $\alpha_X$ \textsuperscript{b} & $N_{\text{H,pc}}$ \textsuperscript{c} & $f_{\text{pc}}$ & $kT$ \textsuperscript{d} & $\chi^2$/dof & $F_{0.3\text{-}10.0\text{keV}}$ \textsuperscript{e} \\
\hline
zp1 + pow1 & 1.00 (fixed) & $26^{+3.5}_{-5.0}$ & $0.95^{+0.02}_{-0.01}$ & $\ldots$ & 83/65 & 20.6 \\
bb + pow1 & $-1.56^{+0.14}_{-0.16}$ & $\ldots$ & $\ldots$ & $163^{+29}_{-19}$ & 74/62 & 13.5 \\
\hline
\end{tabular}
\textsuperscript{a} All fits include absorption by neutral gas in our Galaxy with an absorption column density $N_{\text{H,gal}} = 1.3 \times 10^{21}$ cm$^{-2}$ (Dickey & Lockman 1990).
\textsuperscript{b} Energy spectral index $\alpha_X$.
\textsuperscript{c} Intrinsic absorption column density at the location of NGC 2207/IC 2163 ($\mu = 0.00941$) in units of $10^{22}$ cm$^{-2}$.
\textsuperscript{d} Blackbody temperature $kT$ in units of eV.
\textsuperscript{e} 0.3–10.0 keV flux corrected for Galactic and intrinsic absorption, in units of $10^{-14}$ erg s$^{-1}$ cm$^{-2}$.
\end{table}

Notes.

For this model, the fit is acceptable ($\chi^2$/dof $= 83/65$) and yields for the partial-covering absorber a column density of $N_{\text{H,pc}} = 2.7 \times 10^{21}$ cm$^{-2}$ and covering fraction of $f_{\text{pc}} = 0.95$, as listed in Table 8. The lower left panel of Figure 10 displays the contour plot between the column density and the covering fraction of the absorber. From this model, we derived an unabsorbed flux in the observed 0.3–10.0 keV band of $2.1 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$, which converts to a luminosity of $0.4 \times 10^{41}$ erg s$^{-1}$ in the 0.3–10.0 keV band. This is the luminosity of a low-luminosity Seyfert galaxy, most-likely a Seyfert 2 galaxy. There is excess emission at energies below 1 keV, which can be interpreted as strong emission lines from ionized gas. Such emission lines from ionized gas have been reported in several cases of partial-covering absorption sources, such as the narrow-line Seyfert 1 galaxies Mkn 1239 and Mkn 335 (Grupe et al. 2004, 2007, 2008) or the Seyfert 2 galaxy NGC 5643 (Guainazzi et al. 2004). Our data, however, do not allow us to constrain any parameters of this ionized gas.

The pn and MOS spectra can be fitted alternatively by an absorbed blackbody plus power-law model with no intrinsic absorption. This fit is shown in the upper right panel of Figure 10 and listed in Table 8. The lower right panel of Figure 10 displays the blackbody and the power-law components separately.
blackbody temperature is \( kT = 163^{+29}_{-19} \text{eV} \) and the energy spectral index \( \alpha_X = -1.56^{+0.14}_{-0.16} \) with \( \chi^2/\text{dof} = 74/62 \). Still, the residuals below 1 keV remain. Although the \( \chi^2/\text{dof} \) of the blackbody plus power-law model suggests a slightly better fit compared with the partial-covering absorber model, an \( F \)-test shows this is only a slight improvement (\( F \)-value = 2.51 and a probability of a null random result \( P = 0.067 \)). The energy spectral slope of the hard X-ray power law is unphysically flat, i.e., would require too many higher energy relativistic electrons compared to lower energy relativistic electrons. Therefore, we conclude that the most likely model to explain the X-ray spectrum of the nucleus of NGC 2207 is the power-law model with partial-covering absorption.

The nucleus has an H\( \alpha \) flux of \( 1.58 \times 10^{-14} \) erg s\(^{-1}\) cm\(^{-2}\) and a \( \lambda 6 \) cm flux density of 0.37 mJy (equivalent to a \( \lambda 6 \) cm radio continuum luminosity of \( 5 \times 10^{19} \) W Hz\(^{-1}\)). These values are similar to those of the eyelid clump IR 10. Half of the clumps in Table 3 have greater values of the \( \lambda 6 \) cm flux density than the NGC 2207 nucleus, and thus the nucleus is relatively radio quiet for an AGN.

6.4. Source X1

Figure 11 provides a detailed view of X-ray source X1 with X-ray contours from the MOS data overlaid on the \( HST \) B-band image in the right panel. The plus sign marks the location of the unresolved, non-thermal radio continuum clump rc1, and the width of the plus sign is the HPBW of the \( \lambda 6 \) cm synthesized beam. The main X-ray emission is centered on a collection of blue star clusters, the most prominent of which lies close to the discrete radio source. With \( A_e/N_{\text{gas}} = 0.53 \times 10^{-21} \) mag atom\(^{-1}\) cm\(^{-2}\) from Bohlin et al. (1978) for solar neighborhood metallicity, the intrinsic X-ray absorption column density of X1 is equivalent to \( A_e = 0.6^{+1.1}_{-0.6} \) mag. The value of the \( 8 \mu\text{m} \) to UVM2 flux density ratio (see Section 4) suggests that the clump rc1 suffers little extinction. Other evidence of low extinction is the close resemblance between the B band and UVM2 images. The H\( \text{i} \) line profiles obtained by Elmegreen et al. (1995b) show no evidence for an absorption feature at rc1, but the H\( \text{i} \) data has low spatial resolution of \( 13' 5 \times 12'' \).

Fitting a two-dimensional Gaussian plus a flat baseline to the unresolved source rc1 on our \( \lambda 6 \) cm radio continuum image with \( 2'5 \) resolution gives \( S_\nu(6 \text{ cm}) = 1.12 \pm 0.03 \) mJy. If the radio source rc1 is in NGC 2207 (rather than a background quasar) and is isotropic, it has a \( \lambda 6 \) cm radio continuum luminosity \( L_\nu(6 \text{ cm}) = 1.6 \times 10^{20} \) W Hz\(^{-1}\), which is \( 230 \times L_\nu(6 \text{ cm}) \) of Cas A (taking \( L_\nu(6 \text{ cm}) \) of Cas A as \( 7 \times 10^{17} \) W Hz\(^{-1}\) from Weiler et al. 1989). This \( \lambda 6 \) cm luminosity lies in the range of radio supernovae and in the range of the very brightest SNRs. Neff & Ulvestad (2000) find the three brightest, discrete, non-thermal radio sources in the Antennae merger pair have \( L_\nu(6 \text{ cm}) \) in the range \( 8 \times 10^{19} \) to \( 2 \times 10^{20} \) W Hz\(^{-1}\) and attribute these to SNRs. Each is slightly extended in their high-resolution radio continuum observations. The brightest of these Antennae SNRs is listed as a ULX candidate by Swartz et al. (2004) with a \( L_\nu \) in the \( 0.5–8 \) keV band of \( 18 \pm 11 \times 10^{39} \) erg s\(^{-1}\) and \( \Gamma = 2.54 \), i.e., similar in X-ray spectrum and somewhat more luminous in X-rays than our source X1, which has \( L_\nu = 7 \times 10^{39} \) erg s\(^{-1}\).

Possible interpretations of the source X1/rc1 are a radio supernova, an SNR, a background quasar, or a chance superposition of a ULX in NGC 2207 with a background radio quasar. It is clear from Figure 6 that rc1 was brighter on 2003 January 14 when the \( \lambda 3.5 \) cm (8.46 GHz) radio continuum observations were taken than on 1990 October 11 when the line-free \( \lambda 20 \) cm radio continuum observations were made: in the \( \lambda 3.5 \) cm image, rc1 is much brighter than every other source in the galaxy pair except feature i, whereas no local surface brightness peak is seen at the location of rc1 in the \( \lambda 20 \) cm radio continuum image. Also, no local surface brightness peak at rc1 is visible in the figure in Condon (1983), which displays a \( \lambda 20 \) cm radio continuum image of NGC 2207/IC 2163 with \( 7'6 \times 6'' \) resolution. For a quantitative comparison, we measured the flux density of a \( 21' \times 21'' \) box centered on rc1 in the above \( \lambda 3.5 \) cm image and in a \( \lambda 6 \) cm image made from the UV data used in Figure 1, i.e., B configuration (high-resolution) observations on 2001 April 14 plus D configuration (low-resolution) observations on 1995 May 13. For the \( 21' \) box, \( S_\nu(6 \text{ cm}) = 3.38 \) mJy and \( S_\nu(3.5 \text{ cm}) = 3.26 \) mJy. Part of this flux density is from emission unrelated to rc1. The \( \lambda 6 \) cm flux density unrelated to rc1 in this box equals \( 3.38 \) mJy – 1.12 mJy = 2.26 mJy (where \( S_\nu(6 \text{ cm}) = 1.12 \) mJy for rc1, as measured on the high-resolution image). If the spectral index \( \alpha \) of the unrelated emission lies in the range \( 0.1–0.9 \), then scaling the 2.26 mJy from \( \lambda 6 \text{ cm} \) to \( \lambda 3.5 \text{ cm} \) gives \( S_\nu(3.5 \text{ cm}) = 3.26 \) mJy of the
NGC 2276 is a member of a small group of galaxies embedded in a large diffuse, intragroup, X-ray cloud. Unlike the NE radio ridge in NGC 2207, the large-scale bow-shock-like radio continuum ridge along the western edge of NGC 2276 is a site of active star formation and bright X-ray emission, visible in the Chandra observations by Rasmussen et al. (2006) and the ROSAT High-Resolution Image by Davis et al. (1997). The stellar and gaseous disks in NGC 2276 truncate just beyond this shock-like feature, whereas the NE radio ridge in NGC 2207 is not the outermost spiral arm on the affected side of NGC 2207. The lopsided appearance of NGC 2276 has been attributed either to a tidal interaction with the elliptical galaxy NGC 2300 (Hummel & Beck 1995; Davis et al. 1997) or to ram pressure from the hot intragroup gas (Rasmussen et al. 2006). From Chandra X-ray observations, Rasmussen et al. (2006) find that NGC 2276 is moving supersonically at 850 km s$^{-1}$ through the hot intragroup gas and that the ram pressure, which may have been acting for several $10^9$ yr, could explain the observed compression of the H$\alpha$ gas and magnetic fields along the western edge of NGC 2276, leading to active star formation in this region. They argue that the X-ray emission from the western edge of NGC 2276 is dominated by hot plasma resulting from the vigorous star formation. This may be the reason why the NE radio ridge in NGC 2207 is not bright in X-rays, since it is not a site of extended vigorous star formation. If the scraping between NGC 2207 and IC 2163 and the bright radio continuum emission from the NE radio ridge are high off the disk of NGC 2207, this would explain why the observed H$\alpha$ column density contours are not unusually compressed on the NE radio ridge and why there is no widespread active star formation there.

8. FEATURE $i$

Feature $i$ is the most luminous radio continuum, 8 $\mu$m, 24 $\mu$m, and H$\alpha$ source in the galaxy pair. Figure 12 displays the contours of emission from feature $i$ and environs in various wavebands overlaid on the HST B-band image from observations made in 1996. As shown in this figure, feature $i$ is bright in $\lambda6$ cm radio continuum and 8 $\mu$m emission but highly absorbed in the UVM2 band. Comparison of the UVM2 and 8 $\mu$m images of this region provides an extinction map. Elmegreen et al. (2000) point out the opaque (optically thick even in the I band) conically shaped dust cloud (labeled here) with a bright compact cluster at its apex. The core of the radio source and the brightest 8 $\mu$m and 24 $\mu$m emission are centered on this cluster. The UVM2 emission from the radio core and the conical dust cloud is highly absorbed and no X-ray emission is detected from either (see Figure 12).

In the radio continuum, feature $i$ is a core plus envelope source. Aside from a northern plume in the radio, it looks very similar in the $\lambda6$ cm and 8 $\mu$m images: the extended emission fills a triangular region with E–W base 8$''$ and N–S height 9.6$''$ ($=1.4$ kpc $\times$ 1.7 kpc), which includes the cluster arcs of Elmegreen et al. (2000) and two super-star clusters identified by Elmegreen et al. (2001). Just north of the filled triangular region, the $\lambda6$ cm emission forms a plume with position angle P.A. $=5^\circ$, whereas the 8 $\mu$m emission is a little west of north, i.e., along the arm at P.A. $=-15^\circ$. We take as the definition of feature $i$ the filled triangular region plus the radio plume. It has $S_\nu(6 \text{ cm}) = 4.67$ mJy.

We fit a simplified model consisting of the sum of two two-dimensional Gaussians plus a flat baseline to the $\lambda6$ cm emission from feature $i$ to represent the core plus envelope plus general arm emission. Table 9 lists the results obtained by using our $\lambda6$ cm image with the circular $2^\prime5$ synthesized beam and the
Figure 12. Overlays on the HST B-image of feature i at different wavelengths. The upper left panel displays the contours of the X-ray emission, the upper right the UVM2 data from the XMM-Newton OM observations, the lower left the 8 μm Spitzer observations, and the lower right displays the λ6 cm radio continuum emission. The 8 μm contours are at 2...2, 10...10, 40, 60, 80, and 100 MJy sr⁻¹. The λ6 cm radio contours are at 4...48, 16, 32, 64, and 128 times the rms noise of 0.016 mJy beam⁻¹. The label SN points to a stellar image at the SW edge of the r = 0'3 error circle that Van Dyk et al. (2003) give for the position of SN 1999ec; they conclude that this star is too bright to be the progenitor.

From VLA B configuration snapshot observations in 1986, Vila et al. (1990) measured S(6 cm) = 1.4 mJy for the 1'' core and 3.4 mJy for feature i as a whole, whereas our combined VLA λ6 cm data from B configuration (high-resolution) observations in 2001 and D configuration (low-resolution) observations in 1995 give 2.66 mJy for the 1'' core and 4.66 mJy for feature i as a whole on our highest resolution image (see Table 9), i.e., 1.3 mJy greater than the Vila et al. value for the core and 1.3 mJy greater than the Vila et al. value for feature i as a whole. Differences in flux density can arise from the missing short spacings and higher noise in the Vila et al. data and different ways of measuring the source. However, since the difference in flux density between 1986 and 2001 is the same for the core and for feature i as a whole and the λ6 cm flux density of the core in 2001 is nearly twice the Vila et al. value, we conclude that the λ6 cm flux density of the core increased by 1.3 mJy between 1986 and 2001. This corresponds to an increase in L(6 cm) of 1.9 × 10²⁰ W Hz⁻¹ if isotropic. As this lies in the

Table 9

Gaussian Fits to λ6 cm Emission from Feature i

| Beam HPBW       | Core   | Envelope   | FWHM, P.A. | FWHM, P.A. |
|-----------------|--------|------------|------------|------------|
| 2'50 x 2'50     | 5.90 ± 0.03 | 1.74 x 1.70, 39° | 1.69 ± 0.05 | 5.6 x 1.7, 142° |
| 2'48 x 1'30     | 6.66 ± 0.02 | 1.72 x 0.7, 43° | 2.00 ± 0.07 | 5.5 x 2.6, 145° |

results obtained by using our original λ6 cm image which has higher resolution in the E–W direction (synthesized beam = 2'48 x 1'30 and BPA = 8°). These Gaussian models give for the core plus envelope S(6 cm) = 4.6 ± 0.07 mJy; attribute roughly 60% of the emission to the core, and find the core is slightly elongated along the same line as the opaque dust cloud (position angles 40° for the core and about 40° + 180° for the dust cloud). The opaque dust cloud has a projected length of 2''−3'' (about twice the diameter of the radio core).
luminosity range of radio supernovae, it seems likely that in 2001 a radio supernova was present in the core. From these data, we cannot determine the year when outburst in the core of feature i occurred; Weiler & Sramek (1988) point out examples of radio supernovae that remained bright in the radio for a number of years. A supernova in the core of feature i may have been hidden from view optically by the high extinction. If our interpretation is correct, then NGC 2207 is remarkable in having had two optical supernovae (SN 1999ec and SN 2003H, both Type Ib) plus one radio supernova in recent years (i.e., between 1986 and 2003) and all with high-mass progenitors.

The simulation models by Elmegreen et al. (1995a) and Struck et al. (2005) for the NGC 2207/IC 2163 encounter estimate the inclination i of the main disk of NGC 2207 as 25°–35° (relative to face-on) with the minor axis of the projection at P.A. = 50°–70°. The near side (relative to us) of NGC 2207 is the northeastern side. The opaque dust cloud is aligned nearly parallel to the minor axis of the projection of the main disk of NGC 2207 into the sky plane. Elmegreen et al. (2000) point out a red V-shaped structure with apex at the radio core and opening to the north (see Figure 6 of that paper). The left fork of the V appears to be a continuation of the opaque dust cloud to the opposite side of the core, whereas the right fork of the V is aligned with the inside edge of the optical arm farther north, but straighter than most spiral-arm dust lanes, possibly as a result of extra compression of the original dust lane by the energetic events in feature i. The radio plume is midway between the two forks of the V. Given the orientation of the main disk of NGC 2207, the opaque dust cloud plus the left fork of the V could be outflow perpendicular to the plane of NGC 2207, generated at the radio core, i.e., the dark dust cone could be gas approaching us on the near side (relative to us) of the midplane and the left fork of the V could be gas receding from us on the far side and thus less prominent as an absorption feature because it is not obscuring light on the near side of the midplane.

Elmegreen et al. (2006) measure a 24 μm flux density \( S_{\text{24}}(24 \mu m) = 248 \text{ mJy} \) for the 24° × 24° field displayed in Figure 12. In the HiRES 24 μm image in Velusamy et al. (2008, which has a resolution of 1′′9, a little better than that of the 8 μm and 2.6 cm images shown here), this flux density comes from a 7′5 × 7′5 region centered on the radio core of feature i. This gives a 24 μm to 2.6 cm flux density ratio for feature i of 248 mJy/4.67 mJy = 53, which is somewhat greater than the mean value \( S_{\text{24}}(24 \mu m)/S_{\text{2.6}}(6 \text{ cm}) = 36 ± 9 \) for the M81 H II regions in Table 4 but similar to that of the most luminous giant radio H II region (K181) in M81. In Section 4 (see also Figure 5), we found that feature i is underluminous at 8 μm relative to its 2.6 cm radio continuum emission when compared with the mean value for the M81 H II regions and with the mean value for clumps in NGC 2207 containing OB associations. For feature i, \( S_{\text{24}}(24 \mu m)/S_{\text{2.6}}(8 \mu m) = 248 \text{ mJy}/35 \text{ mJy} = 7.1 \), which is high compared to the mean value of 1.9 for the M81 H II regions in Table 4 and compared to the mean value for the SINGS sample (see Table 5), but similar to that of the dwarf (1m) starburst galaxy Mrk 33, which has \( S_{\text{24}}(24 \mu m)/S_{\text{2.6}}(8 \mu m) = 6.6 \) (Dale et al. 2007). Emission at 24 μm is from warm very small grains, whereas emission at 8 μm is a combination of PAH emission bands and continuum emission from warm very small grains. The high value of the 24–8 μm flux density ratio of feature i and the low value of the 8 μm to 2.6 cm flux density ratio suggest some PAH destruction by the radiation field of feature i has depressed its 8 μm emission.

In the HiRES 24 μm image in Velusamy et al. (2008), feature i appears as a filled elliptically shaped region with minor axis/major axis ratio = 0.8 and minor axis at P.A. = 50°. Given the orientation of the disk of NGC 2207, it is probably a filled circular region in the disk of NGC 2207.

A long-slit optical spectrum taken by P. Martin (2000, private communication) with the Canada–France–Hawaii Telescope MOS prior to 2000 cuts E–W through the core of feature i and exhibits a normal H II region spectrum with no unusual line ratios. The long-slit optical spectrum of SN 1999ec (8° south-southeast of the radio core) taken by Matheson et al. (2001) has a P.A. of −17°, a resolution of 6.3 Å (380 km s\(^{-1}\)) FWHM at 5000 Å, includes cluster arcs in feature i, and crosses the east fork of the red V. North of SN 1999ec, this spectrum shows normal H II region emission but the line profiles have a little asymmetry with a slightly more extended red wing, i.e., for the [O III] \( \lambda 5007 \) line, the center of a Gaussian fit is shifted systematically to the red relative to the intensity maximum with the shift increasing from 0.2 ± 0.3 Å at the southern cluster arcs to 0.6 ± 0.3 Å at the east fork of the red V. This may be an instrumental effect associated with non-centered sources projecting onto different positions on the chip. The optical emission-line velocities are generally consistent with the H I velocities given that the H I data from Elmegreen et al. (1995b) has low spatial resolution and a velocity dispersion of 56 km s\(^{-1}\) at feature i. Neither of these optical spectra is suitable for looking for low-velocity outflows from feature i. At the feature i positions sampled by these two long slits, photoionization dominates, and these optical spectra show no components in feature i at supernova or jet velocities.

Since photoionization dominates the optical spectra whereas the radio emission is nonthermal, we interpret feature i as a mini-starburst and compare it with the central starburst in M82. The central 50° × 15° starburst in M82 has \( S_{\text{8}}(6 \text{ cm}) \) equal to 3.4 ± 0.2 Jy (Hargrave 1974), a radio spectral index α of 0.5, and outflow over a wide range of solid angle (Seaqquist & Odegard 1991). If the M82 central starburst were at the 35 Mpc distance of NGC 2207 instead of 3.6 Mpc, it would have a major axis of 5′1 (a little smaller than feature i) and \( S_{\text{8}}(6 \text{ cm}) \) = 36 mJy, which is 7.7 times the λ6 cm flux density of feature i as a whole. Except in the 1′ core of feature i, the λ6 cm radiation field in feature i is significantly less intense than the average value for the M82 starburst. We estimate the value of \( S_{\text{8}}(24 \mu m)/S_{\text{8}}(6 \text{ cm}) \) of the central starburst in M82 for comparison with feature i. With a 25′ aperture centered on the M82 starburst, Kleinman & Low (1970) measured \( S_{\text{8}}(22 \mu m) = 120 \text{ Jy} \). Extrapolating to 24 μm by taking \( I_{\nu} \propto \nu^{-1} \) gives \( S_{\text{24}}(24 \mu m), \) = 130 Jy for a 25′ aperture. For the 50′ extent of the radio emission from the M82 starburst, \( S_{\text{8}}(24 \mu m) \) should be somewhat greater than 130 Jy, and thus \( S_{\text{8}}(24 \mu m)/S_{\text{8}}(6 \text{ cm}) \) should be somewhat greater than 130 Jy/3.4 Jy = 38. It appears that the ratio \( S_{\text{8}}(24 \mu m)/S_{\text{8}}(6 \text{ cm}) = 53 \) for feature i is not unusual for a dusty starburst region.

The upper left panel in Figure 12 displays contours of the X-ray emission from source X2. The core of feature i is not detected as an X-ray source. The absence of soft X-rays could be the result of the high absorption seen from comparison of the UVM2 and 8 μm images. The X-ray emission is generally south and south-southeast of feature i, and the brightest X-ray knot is centered 2′4 north of SN 1999ec. The upper right panel in this figure shows that the UVM2 peak emission coincides with the supernova. As previously reported by Pooley (2007) from an archival search of Type Ib,c supernovae which used our
XMM-Newton observations of NGC 2207, it seems likely that most of the X-ray emission from X2 is associated with the Type Ib supernova SN 1999ec. It is unusual for a Type Ib supernova to be seen as an X-ray source, and, interestingly, SN 1999ec is bright in X-rays 6 years after the optical SN was discovered. The X-ray emission may be from the supernova shock plowing into a circumstellar envelope. This makes it more plausible that the bright UVM2 emission coinciding with SN 1999ec is due to shock excitation of circumstellar gas by the supernova. The X-ray spectral index of X2 is steeper than typical of an X-ray binary.

9. CONCLUSIONS

We presented the X-ray and UV data observed by XMM-Newton and new 6 cm radio continuum observations of the interacting galaxies NGC 2207/IC 2163. When combined with our previous observations in Hα, HST B band, Spitzer infrared, H1, and SEST $^{12}$CO $J = 1 \rightarrow 0$ and with Swift/XRT observations, these data allow us to see the effects of the grazing encounter in producing large-scale shocks, to study star complexes, supernovae, and the galactic nuclei in this pair, and to identify possible ULX candidates.

In X-rays we detect the nucleus of NGC 2207, nine possible ULX candidates, and extended X-ray emission, mainly from NGC 2207. One of the discrete X-ray sources corresponds to SN 1999ec and another has brightened in the radio in recent years and could be a radio supernova or a background quasar. The bright UVM2 and X-ray emission from SN 1999ec may be from shock excitation of circumstellar gas by the supernova. The strongest source in our XMM-Newton X-ray observations of NGC 2207/IC 2163 is the nucleus of NGC 2207. It is the only hard X-ray source in the field. The preferred model for its X-ray spectrum is a power law with a partial-covering absorber. Most likely this is a strongly absorbed, low-luminosity, Seyfert 2 AGN. However, optical spectroscopy is needed to confirm this assumption.

We measured values of the ratio of X-rays to 6 cm radio continuum flux density for the prominent, kiloparsec-size, star-forming clumps in the galaxy pair and compared them with those for the M81 H II regions whose radio continuum is dominated by optically thin free–free emission. For the bright clumps in NGC 2207, the mean value of this ratio equals 18, which is the same as for giant radio H II regions in M81, within the uncertainties. For the bright clumps on the rim (the eyelids) of the eye-shaped oval in IC 2163, the mean value is nearly a factor of two greater.

There are two types of large-scale fronts in this galaxy pair: the eyelids of the eye-shaped oval in IC 2163 and the NE radio ridge on the companion side of NGC 2207. Simulations suggest that the eyelid shock front is produced by both inflow and outflow, resulting in a convergence of orbits with vigorous star formation in a dusty environment. In the eyelids, the ratio of the 8 μm to 6 cm surface brightness is two times greater than in the NGC 2207 and M81 giant H II regions. This excess 8 μm emission could be the result of heating of PAHs by the current generation of OB stars in the H II regions, in addition to an equal amount of heating by B stars in the same region from the previous ∼30 Myr of star formation. Unlike the flow of older stars through a steady spiral density wave, an ocular front should accumulate mass as it grows stronger. The excess 8 μm emission could also result from shock-heated H$_2$ emission or from fragmentation of dust grains down to PAH sizes by collisions in the shock region. The eyelids are located behind the outer part of NGC 2207; this may explain why they are not bright in extended soft X-ray emission.

The NE radio ridge in NGC 2207 is particularly bright in the radio continuum but not in any of the tracers of recent star formation. Values of the ratios of 8 μm to 6 cm surface brightness and 24 μm to 6 cm surface brightness are low on the NE radio ridge compared to those of the M81 H II regions. Unlike the bright radio ridge in the outer part of NGC 2276, the NE radio ridge is not enhanced in extended X-ray emission relative to the rest of the galaxy; this is probably because it is not a site of active star formation. The NE radio ridge, which previous models attributed to disk or halo scraping, is simply due to compression of the magnetic field and may be mainly in the halo on the back side of NGC 2207 (between the two galaxies). The X-ray flux of the NE radio ridge provides an upper limit of 0.036–0.081 cm$^{-2}$ to the density of halo gas there if the line-of-sight path length through the shocked gas in the halo is 1–5 kpc. Having the bright radio continuum emission from the NE radio ridge originate high off the disk of NGC 2207 in a region with little neutral gas explains the lack of widespread vigorous star formation and the lack of unusually compressed H1 column density contours on the NE radio ridge.

For NGC 2207/IC 2163, the global values of the ratios of infrared-to-radio continuum flux density in the Spitzer 8 μm, 24 μm, and 70 μm bands, and the IRTF/FIR are significantly below the medians/means for large samples of galaxies. This is the result of excess radio continuum emission from large portions of NGC 2207, not just the NE radio ridge.

We find evidence that a radio supernova was present in the core of feature i in 2001. If so, then NGC 2207 had two optical supernovae and one radio supernova in recent years. The 6 cm radio continuum luminosity of feature i on an outer arm of NGC 2207 is 13% of the central starburst in M82. In linear size, feature i is a little larger than the M82 starburst. Like the M82 starburst, feature i is a dusty starburst region with radio continuum emission that is mainly non-thermal and with a 24 μm to 6 cm flux density ratio somewhat greater than the mean value for the M81 giant H II regions. Whereas the M82 starburst has outflow perpendicular to the disk which is bright in X-rays, our only indication of outflow perpendicular to the disk in feature i is the peculiar morphology of the dust structures.

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