MOLECULAR GAS AND THE MODEST STAR FORMATION EFFICIENCY IN THE “ANTENNAE” GALAXIES: ARP 244 = NGC 4038/9

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Received 2000 July 19; accepted 2000 October 9

ABSTRACT

We report here a factor of 5.7 higher total CO flux in Arp 244 (the “Antennae” galaxies) than that previously accepted in the literature (thus a total molecular gas mass of \(1.5 \times 10^{10} M_\odot\)), based on our fully sampled CO(1–0) observations at the NRAO 12 m telescope. Currently, much of the understanding and modeling of the star formation in Arp 244 has been derived using a much lower molecular gas mass. It is imperative to reconsider everything, as the high molecular gas mass might provide sufficient fuel for ultraluminous extreme starburst in Arp 244 once the merging advances to late stage.

Our observations show that the molecular gas peaks predominately in the disk-disk overlap region between the nuclei, similar to the far-infrared (FIR) and mid-infrared (MIR) emission. The bulk of the molecular gas is forming into stars with a normal star formation efficiency (SFE) \(L_\text{IR}/M_\text{H_2} \approx 4.2 L_\odot/M_\odot\), the same as that of giant molecular clouds in the Galactic disk. Additional supportive evidence is the extremely low fraction of the dense molecular gas in Arp 244, revealed by our detections of the HCN(1–0) emission, which traces the active star-forming gas at density \(\gtrsim 10^4 \text{ cm}^{-3}\).

Using the high-resolution BIMA + NRAO 12 m telescope, full-synthesis CO(1–0) images and our VLA continuum maps at 20 cm, we estimate the local SFE indicated by the ratio map of the radio continuum to CO(1–0) emission, down to kiloparsec scale. Remarkably, the local SFE stays roughly the same over the bulk of the molecular gas distribution. Only some localized regions show the highest radio-to-CO ratios that we have identified as the sites of the most intense starbursts with SFE \(\gtrsim 20 L_\odot/M_\odot\). Here we have assumed that the 20 cm emission is a fairly good indicator of star formation down to kiloparsec scale in Arp 244 because of the well-known correlation between the FIR and the radio continuum emission. These starburst regions are confined exclusively to the dusty patches seen in the Hubble Space Telescope optical images near the CO and FIR peaks where the violent starbursts are presumably heavily obscured. Nevertheless, recent large-scale star formation is going on throughout the system (e.g., concentrations of numerous super–star clusters and MIR “hotspots”), yet the measured level is more suggestive of a moderate starburst (SFE \(\gtrsim 10 L_\odot/M_\odot\)) or a weak to normal star formation (SFE \(\sim 4 L_\odot/M_\odot\)), not necessarily occurring at the high concentrations of the molecular gas reservoir.

The overall starburst from the bulk of the molecular gas is yet to be initiated as most of the gas further condenses into a kiloparsec scale in the final coalescence.

Subject headings: galaxies: individual (NGC 4038/9) — galaxies: interactions — galaxies: starburst — infrared: galaxies — ISM: molecules — stars: formation

On-line material: machine-readable table

1. INTRODUCTION

The “Antennae” galaxies (Arp 244, NGC 4038/9, VV 245), the nearest IR-luminous and perhaps the youngest prototypical galaxy-galaxy merger (the first in the Toomre [1977] merger sequence), certainly reclaimed their fame from the recent releases of the Hubble Space Telescope (HST)/WFPC2 images (Whitmore et al. 1999) and the Chandra X-ray images (Fabbiano et al. 2000) and the observations at essentially all available wavelengths from radio to X-ray (e.g., Hummel & van der Hulst 1986; Neff & Ulvestad; Hibbard, van der Hulst, & Barnes 2001, in preparation) Bushouse; Telesco, & Werner 1998; Nikola et al. 1998; Mirabel et al. 1998; Vigroux et al. 1996; Read, Ponman, & Wolstencraft; Fabbiano, Schweizer, & Mackie 1997). The HST images reveal over 1000 bright young star clusters that are thought to have formed in recent bursts of star formation. Hz imaging also shows the most recent locations of the star-forming giant H II regions and their velocity fields as well (Rubin, Ford, & D’Odorico 1970; Amram et al. 1992; Whitmore et al. 1999). Soft X-ray (Fabbiano et al. 1997) and radio continuum (Hummel & van der Hulst 1986) images may hint of previous star formation sites currently seen as supernova remnants. In addition, mid-infrared (MIR) (Mirabel et al. 1998; Vigroux et al. 1996), far-infrared (FIR) (Evans, Harper, & Helou 1997; E. Evans 1998, private communication; Bushouse et al. 1998), and submillimeter (Haas et al. 2000) images indicate that the most intense starburst takes place currently in an off-nucleus region that is inconspicuous at optical wavelengths. The star-forming molecular gas in Arp 244 is perhaps the least understood, however, as we show in this paper that the total molecular gas mass accepted in the literature for the last decade (Sanders & Mirabel 1985; Stanford et al. 1990) has been underestimated by nearly a factor of 6.
The importance of gas during galaxy–galaxy merging far exceeds its mass proportion, as demonstrated by the sophisticated numerical simulations (e.g., Barnes & Hernquist 1996, 1998). At a distance of 20 Mpc ($H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$; e.g., van der Hulst 1979; Mihos, Bothun, & Richstone 1993; Mirabel et al. 1998), the total IR luminosity (8–1000 μm; Sanders & Mirabel 1996) of Arp 244, measured from the IRAS four-band fluxes given in Soifer et al. (1989), is $L_{\text{IR}} = 6.2 \times 10^{10} L_\odot$. Using the most recent remeasured total IRAS fluxes (as opposed to simply the “point source” in Soifer et al. 1989) in the Revised Bright Galaxy Sample (D. B. Sanders 2000, private communication; Sanders et al. 2001, in preparation), the same IR luminosity is obtained. Therefore, strictly speaking, Arp 244 is not a luminous infrared galaxy (LIG; $L_{\text{IR}} \gtrsim 10^{11} L_\odot$) unless a Virgocentric flow distance of 29.5 Mpc is used (Sanders et al. 2001, in preparation; but we use 20 Mpc throughout this paper), which leads to and now distance of 29.5 Mpc is used (Sanders et al. 2001, in preparation), the same IR luminosity is obtained. This ratio is often referred as the star formation efficiency (SFE) since the FIR emission, the tracer of current star formation rate, has been normalized by the molecular gas mass available to make stars. With this high yield of young stars per unit molecular gas mass and a lower molecular gas content, most of the molecular gas will be depleted in ~10$^8$ yr, as noted by Sanders & Mirabel (1985) and Stanford et al. (1990). There would be no chance for Arp 244 to become an ultraluminous infrared galaxy (ULIG; $L_{\text{IR}} \gtrsim 10^{12} L_\odot$) in the late stage of merging. Numerical modeling (Mihos et al. 1993), based on this lower gas mass, indeed predicted that Arp 244 would not join the rank of ULIGs.

ULIGs, with an IR luminosity comparable to the bolometric luminosity of QSOs, are the most luminous galaxies in the local universe. They are believed to be powered mainly by starbursts (e.g., Smith, Lonsdale, & Lonsdale 1998; Genzel et al. 1998) taking place predominantly in the extreme starburst regions of a characteristic size of ~100 pc and $L_{\text{IR}} \sim 3 \times 10^{11} L_\odot$ (Downes & Solomon 1998), produced as a result of the merging of molecular gas-rich spiral galaxies (Sanders & Mirabel 1996). Alternatively, the dust-shrouded active galactic nuclei (AGNs) may still be responsible for significant energy output in some ULIGs (Sanders et al. 1988; Veilleux, Sanders, & Kim 1999; Sanders 1999). Now, for a total molecular gas mass of $1.5 \times 10^{10} M_\odot$, based on our fully sampled CO(1–0) observations obtained at the NRAO 12 m telescope, many previous conclusions and speculations about Arp 244 need to be revised. After all, the initial gas content, particularly the molecular gas—the fuel for star formation—will probably be the most important factor in determining whether a merging pair of spiral galaxies reaches the peak of ultraluminous extreme starburst phase since all ULIGs are still gas rich, with ~$10^{10} M_\odot$ molecular gas mass (Solomon et al. 1997), most likely concentrated in the kiloparsec-scale disks/rings around the merging nuclei (Downes & Solomon 1998; Scoville, Yun, & Bryant 1997; Sakamoto et al. 1999; cf. Evans, Surace, & Mazzarella 2000).

With a molecular gas mass comparable to that of ULIGs and an early/intermediate merging stage, Arp 244 is perhaps an example of what an ULIG might have looked like a few hundred million years ago. Arp 244 may be a snapshot in the evolution of a typical gas-rich merger into an ULIG system. Thus, it is crucial to understand how, where, and when the starbursts initiate or have occurred in such an ongoing merger. This becomes especially imperative in Arp 244, given the advantage of its close-up distance and therefore the better linear resolution available. Nonetheless, the strongest starburst site revealed from the InfraRed Space Observatory (ISO) MIR images (Vigroux et al. 1996; Mirabel et al. 1998; Xu et al. 2000) seems to be offset from the peak emission in all the 60, 100, and 160 μm FIR maps of the limited resolution, obtained with the Kuiper Airborne Observatory (KAO) (Evans, Harper, & Helou 1997; Bushouse et al. 1998). In order to best locate the sites of the intense star formation, high-resolution imaging in the FIR is ultimately required.

Since there is an excellent correlation between the FIR and the radio continuum emission (e.g., Helou, Soifer, & Rowan-Robinson 1985; Condon et al. 1990; Condon 1992; Xu et al. 1994; Marsh & Helou 1995), the FIR emission can thus be approximately scaled according to the radio continuum emission with the high resolution achievable by the Very Large Array (VLA) observations. We have therefore, obtained the VLA radio continuum images to compare with our high-resolution full-synthesis Berkeley-Illinois-Maryland Association (BIMA) plus the NRAO 12 m telescope CO maps. This is because the star formation occurs within giant molecular clouds (GMCs), especially the dense cores, and starburst can be better characterized by the elevated SFE, i.e., the FIR-to-CO ratio, approximated here by the radio-to-CO ratio. Therefore, local SFE across over the merging system can be approximately measured using the ratio map of the radio continuum to the CO emission to locate the most intense starburst sites of the highest radio-to-CO ratios.

We here briefly report our various observations in § 2 detailing the single-dish CO mapping in Arp 244. The BIMA interferometry CO and the VLA 20 cm continuum observations will be presented elsewhere. The observational results and analysis are summarized and compared in § 3. Section 4 discusses the starburst properties of Arp 244 and the implications of our observations. Finally, we conclude with our main results.

2. OBSERVATIONS

We obtained the NRAO 12 m single-dish CO(1–0) map at Nyquist sampling (half-beam spacing ~27.5") in order to determine the true total CO extent and distribution and help add in the zero-spacing flux missed from the multifield BIMA CO(1–0) data cube. A total of more than 50 positions were observed in 1998 March, and 20 more positions in the outer edge of the map were further obtained in 1998 April to fully cover the entire CO emission region. We have essentially integrated for at least 1.5 hr at every position in order to make sure that not only no further ~3 $\sigma$ level CO emission is detected in the outermost edge of the map, but that all spectra obtained at different positions have roughly comparable rms noise level as well. A total of 73 positions have been mapped in the merging disks accumulating more than 110 hr useful integration time. Additional observations in 1999 June and November have been conducted remotely.
in the southeastern (SE) extension of the disk overlap region (where the much longer southern tidal tail starts) and at the tip of the southern tail (Fig. 1). This is to further integrate down the noise level to clearly show that CO is detected significantly far away from the merging disks and to possibly search for CO emission at the location of the tidal dwarf galaxy, several tens of kiloparsecs away from the merging disks. The typical integration time at each of these selected positions is more than 3 hr. We have tried several positions at the tip of the southern tidal tail, and deep integrations in the possibly detected positions were further conducted in 2000 March and April, totaling 27 hr usable integration time in this tidal feature area.

We used the dual SIS 3 mm hi receivers connected with both the two 256 × 2 MHz filter banks and the two 600 MHz spectrometers providing a velocity resolution of 2 MHz ~ 5 km s\(^{-1}\) and a total velocity coverage of 1330 km s\(^{-1}\). The system temperature \(T_{\text{sys}}\) (SSB) was typically less than 400 K (on a \(T_{\text{sys}}\) scale), and the weather conditions were excellent throughout almost all observing runs. Occasionally, exceptional weather with \(T_{\text{sys}}\sim 200\) K (for a low-declension southern sky source at 115 GHz!) was seen in a few days. All observations were performed using a subreflector nutating at a chop rate of 1.25 Hz with a beam throw of \(\pm 3\)′ plus a position switch (the so-called BSP mode) to achieve the flat baselines. This ensures that the off-source reference sky position is 6′ away from the observed on-source pointing so that the telescope beam (FWHM ~ 55′) at the reference position is well outside the CO extent of Arp 244. Pointing and focus have been monitored frequently every 1–2 hr by observing nearby quasars 3C 279 or 3C 273 (and occasionally planets at the beginning of the observations). Uncertainties in positioning are typically ~ 5′. Calibration with the standard chopper-wheel method was performed once after every other 6 minute integration scan and yielded an antenna temperature on a \(T_{\text{sys}}\) scale. Further absolute flux calibrations in the antenna temperature scale have been performed by the repeated observations of the northern nucleus (our map center) during different observing sessions and by the observations of some nearest well-observed starburst galaxies. Comparing the observed line strengths and profiles, we found that the consistency is satisfactory and the difference is less than ~ 20%.

HCN(1–0) was observed in 1997 April at only two locations: the northern nucleus (NGC 4038) and the CO peaks in the overlap region (Fig. 1). This was part of another project to search for the HCN emission in the LIG mergers. Additional integrations at these two locations were obtained in 1999 November as a further consistency check. The 12 m telescope’s FWHM beam at 89 GHz (~72′), pointed at the nucleus of NGC 4038, presumably covers all HCN emission in NGC 4038, yet excludes emission from that of NGC 4039 and most of the disk overlap region. The second HCN beam covers not only all the CO peaks and the extended CO in the overlap but also most CO emission in NGC 4039. Therefore, the total HCN emission from Arp 244 can be roughly sampled by simply summing up these two beam measurements. \(T_{\text{sys}}\) on a \(T_{\text{sys}}\) scale is about 230 K with the dual SIS 3 mm hi receivers and the same back ends as used in the CO observations. We have accumulated a total integration time of nearly 5 and 7 hr for NGC 4038 and the overlap/NGC 4039, respectively.

Our data reduction was performed using the CLASS/GILDAS package. Each individual scan was checked for spikes/dips or bad channels and curvatures in the baseline. Scans with the structured baselines have been abandoned, bad channels have been “repaired” by interpolation using the adjacent channels, and a linear baseline was then subtracted after removal of the spikes/dips for each accepted scan. All scans at each same position have then been summed to obtain an average spectrum. The data cubes of the different velocity spacings were also created from the highest velocity resolution (2MHz ~ 5 km s\(^{-1}\)) and the smoothed (e.g., 4 MHz ~ 10 km s\(^{-1}\)) spectra maps. All spectra presented in this paper have been smoothed to 8 MHz (~21 km s\(^{-1}\) for CO and ~27 km s\(^{-1}\) for HCN).

3. RESULTS AND ANALYSIS

3.1. Previous CO (1–0) Observations

The currently accepted total molecular gas mass in Arp 244 is based on a single pointing observation with the 12 m in the overlap region. Sanders & Mirabel (1985) listed an integrated intensity of 15.9 K km s\(^{-1}\), or a total CO flux of only 556.5 Jy km s\(^{-1}\) (~35 Jy K\(^{-1}\) on a \(T_{\text{sys}}\) scale), leading to a molecular gas mass of 2.6 × 10\(^{9}\) \(M_\odot\). The Owens Valley Radio Observatory (OVRO) millimeter array’s two overlapping fields (FWHM ~ 65′) CO imaging only recovered ~70% CO flux (Stanford et al. 1990) of the one-beam (FWHM ~ 55′) 12 m measurement! The 12 m beam observed in Sanders & Mirabel (1985) only covered part of the overlap region, neither the nuclear regions of NGC 4038 and NGC 4039 nor the extended structures throughout the entire merging disks (see Figs. 1 and 2). Apparently, much of the CO is distributed over a much larger area than the 55′...
Fig. 2.—Fully mapped NRAO 12 m CO(1–0) integrated intensity map (in contours) overlaid on the HST/WFPC2 image. The contours are 3, 4, 6, to 28 K km s$^{-1}$ (in increases of 2 K km s$^{-1}$ on a $T_K$ scale). The CO spectra at each of the observed position are also plotted (velocity ranges from 1150 to 2050 km s$^{-1}$, and $T_K$ ranges from −25 to 155 mK). The currently accepted total molecular gas mass in the literature was based on only one beam measurement near the CO peak position (Sanders & Mirabel 1985). Obviously, one NRAO 12 m beam (top left) does not capture anywhere even near the CO emission from the overlap region. We have sampled 73 positions at half-beam spacing to ensure that no further extended CO emission was significantly detected in the outer edge, in typically 1.5 hr of integration time.

Young et al. (1995) observed six positions in NGC 4038 and one position in NGC 4039 with the Five College Radio Astronomy Observatory (FCRAO) 14 m telescope (FWHM $\approx 50''$) and derived a total CO flux of $\approx 2070$ Jy km s$^{-1}$ assuming a uniform CO disk of radius $\approx 0.6$ for NGC 4038 and an exponential CO disk of scale length $\approx 0.32$ for NGC 4039. Aalto et al. (1995) observed three positions in Arp 244 with the Swedish European Submillimeter Telescope (SEST) (15 m, FWHM $\approx 45''$), i.e., the overlap region and the nuclear regions of NGC 4038 and NGC 4039. A sum of the integrated CO line intensities from the SEST observations leads to a total CO flux close to what has been estimated by Young et al. (1995). Nevertheless, the new OVRO three-field imaging (Wilson et al. 2000) appears to only recover a total CO flux of $910$ Jy km s$^{-1}$, but this is already more than double that of the old OVRO map of Stanford et al. (1990). All these recent measurements of still very limited spatial coverage already suggest that the total CO flux in Arp 244 can be a factor of a few larger than what has been previously accepted.

3.2. New CO(1–0) Observations and the Total Molecular Gas Mass

Figure 2 shows all the averaged CO spectra made with the 12 m telescope at a half-beam spacing, a total of 73 spectra with more than 50 firm detections. Only CO spectra at the outermost edge generally show nondetection or tentative detections (noted in Table 1). Many CO spectra in the inner part of the map (the disk overlap and the two nuclear
regions) have integrated line intensities more than \(\sim 50\%\) larger than that of the old 12 m measurement of Sanders & Mirabel (1985). Observations in 1999 June at the same position as that of Sanders & Mirabel (1985) gave an integrated line intensity exactly twice as large, consistent with those mapped in the nearby positions in 1998 March/April. The northern nucleus was always observed in all observing sessions giving consistent results of about the same integrated CO line intensity. Figure 3 presents the three spectra obtained near the CO peaks in the overlap region and compares them with the original spectrum of Sanders & Mirabel (1985). Obviously, the old 12 m observation may have suffered severely from the poorly determined baseline owing to the limited bandwidth, as the broadest CO spectra in the overlap region have FWZI \(\sim 600\) km s\(^{-1}\). But this is probably insufficient to explain a factor of 2 difference in the integrated CO line intensity. Additional errors in the telescope pointing and calibration together with the limited velocity coverage may have all contributed to the discrepancy.

The total CO flux, from our fully sampled CO observations (summarized in Table 1), is \(S_{\text{CO}}dV = 3172 \pm 192\) Jy km s\(^{-1}\) (\(l_{\text{CO}} = 90.6 \pm 5.5\) K km s\(^{-1}\), using a 35 Jy K\(^{-1}\) conversion for the \(T_{\text{R}}\) antenna temperature scale), a factor of 5.7 larger than what was initially reported by Sanders & Mirabel (1985). The total CO luminosity is thus \(L_{\text{CO}} = 0.3 \times 10^{19}\) K km s\(^{-1}\) pc\(^2\) (\(T_{\text{mb}}\)), or a molecular gas mass \((1.5 \pm 0.1) \times 10^{10}\) \(M_{\odot}\) [using the standard CO-to-H\(_2\) conversion factor of \(3.0 \times 10^{20}\) H\(_2\) cm\(^{-2}\) (K km s\(^{-1}\))\(^{-1}\), or \(M(\text{H}_2) = 4.78 \times (l_{\text{CO}}/\text{K km s}^{-1}\text{pc}^{2})\) \(M_{\odot}\), applicable to GMCs in the Milky Way disk, e.g., Solomon & Barrett 1991; Young & Scoville 1991]. The error estimate is purely from the measurement uncertainties (statistical errors from all measurements and the uncertainties in the CO detections in the outer edge); additional uncertainties up to \(\sim 20\%\) should be expected from the calibration and pointing, etc.

It is interesting to note that the new estimate of the dust mass in Arp 244, based on the SCUBA 450 and 850 \(\mu m\) measurements as well as the ISOPHOT observations at wavelengths longer than 100 \(\mu m\), reveals a substantial amount of cold and warm dust, and leads to a total dust mass of \(M_{\text{dust}} \sim 10^8\) \(M_{\odot}\) (Haas et al. 2000). Thus, for a total gas mass of \(M_{\text{gas}} \sim M(\text{H}_2) + M(\text{H} I) \sim 1.9 \times 10^{10}\) \(M_{\odot}\) \([M(\text{H} I) \sim 4 \times 10^9\) \(M_{\odot}\); van der Hulst 1979; Hibbard et al. 2001, in preparation], a gas-to-dust ratio of \(M_{\text{gas}}/M_{\text{dust}} \sim 190\) is obtained. This is basically the same gas-to-dust ratio established in our Galaxy and in some nearby spiral galaxies such as NGC 891 (Alton et al. 2000). This simple consistency may also imply that the standard CO-to-H\(_2\) conversion determined from GMCs in the Milky Way disk is likely applicable here and Arp 244 is indeed molecular gas rich. Table 2 summarizes the global quantities of Arp 244.

### 3.3 Global Molecular Gas Distribution and Kinematics

Although most of the molecular gas is concentrated in the disk overlap region, the extended distribution of the molecular gas spreads essentially all over the merging disks, much further beyond the field of view of the WFPC2 (Fig. 2). There are also concentrations of the molecular gas in the two nuclear regions, particularly in the northern one. This is better indicated in the quite coarse channel map of 100 km s\(^{-1}\) width (Figs. 4a–4e). In general, there are good correspondences between the CO distribution and the optical morphology, except for the overlap region where the CO emission appears to be much more prominent than the optical light. Figure 4f further compares the CO integrated intensity contours (using all 74 position CO observations) with the optical disks. All these (Figs. 4a–4f) clearly show
that the molecular gas extends throughout the system and explain why the old 12 m single-beam measurement underestimated the total CO emission by a large factor. Obvi-
ously, much of the CO over a broad velocity range is simply distributed over several arcminutes and corresponds to a linear CO extent of possibly beyond ~20 kpc.

The deep integration at the SE edge of the overlap region, where the southern tidal tail begins, confirms the clear detections of the weak CO emission from this region (Fig. 5a). The central offset of the spectra shown in Figure 5a is (110°, -82°:5) relative to the northern nucleus, two full beams further out from the peak emission in the overlap region. CO emission is also detected, for example, at offsets relative to (J2000,R.A.

\begin{table}
\centering
\caption{Table 1 -- Continued}
\begin{tabular}{cccccc}
\hline
Number & R.A.$^a$ (arcsec) & Decl.$^a$ (arcsec) & $I_{CO}^b$ (K km s$^{-1}$) & $V_{CO}$ (K km s$^{-1}$) & $\Delta V_{FWHM}$ (K km s$^{-1}$) \\
\hline
64 & -107.9 & -27.5 & 0.4$^e$ & 1599 & 54 \\
65$^b$ & 110.3 & -82.5 & 1.7 & 1564 & 178 \\
66$^b$ & 110.3 & -82.5 & 3.5 & 1575 & 284 \\
67 & 110.3 & -82.5 & 0.0 & 1629 & 251 \\
68$^b$ & 110.3 & -82.5 & 1.7 & 1564 & 201 \\
69$^b$ & 110.3 & -82.5 & 0.0 & 1629 & 324 \\
70 & 136.8 & -55.0 & 0.4$^e$ & 1588 & 30 \\
71 & 136.8 & -55.0 & 1.2$^e$ & 1644 & 370 \\
72 & 136.8 & -55.0 & 0.5$^d$ & 1520 & 300 \\
73 & 25.9 & -39.1 & 34.3 & 1558 & 209 \\
\hline
\end{tabular}
\end{table}

Note.—Table 1 is also available in machine-readable form in the electronic edition of the Astrophysical Journal.

$^a$ Offsets relative to R.A. = 12°01′53″, Decl. = -18°52′05″ (J2000, the nucleus of NGC 4038).

$^b$ Integrated CO line intensity, which is calculated using the same broad line emission window of 1300 to 1900 km s$^{-1}$. The Jy K$^{-1}$ (T$_{mb}$) conversion adopted is ~35 Jy K$^{-1}$. Some offsets have slightly larger $I_{CO}$ when a narrower line emission window is used.

$^c$ Tentative detections (≤3σ).

$^d$ Non-detections (≤ 3σ).

$^e$ Deep CO spectra are shown in Fig. 5a.

The overall velocity spread of the molecular gas is more than 600 km s$^{-1}$ across the two merging disks. The narrowest velocity ranges are observed in the nuclear region of the northern face-on galaxy NGC 4038 (FWZI ~ 300 km s$^{-1}$, FWHM ~ 100 km s$^{-1}$), while a broader velocity...
spread (FWZI \( \simeq 500 \) km s\(^{-1}\), FWHM \( \sim 230 \) km s\(^{-1}\)) can be seen in the southern inclined galaxy NGC 4039. The broadest velocity components (FWZI \( \sim 600 \) km s\(^{-1}\), FWHM \( \sim 300 \) km s\(^{-1}\)) are particularly prominent south of NGC 4039, even though the CO emission is quite weak (Fig. 2 and Nos. 6, 9, 17, 27, and 29 in Table 1). It is likely that the interferometric observations have almost entirely resolved and thus missed these weak and broad velocity features. The velocity extent around the peak CO emission in the overlap has a similarly broad velocity range. Also, the velocity spread of most spectra in the overlap region lies between the two extremes observed in the two galaxies. This is obvious since some spectra contain the CO contribution from either NGC 4038 or NGC 4039 or both. But clearly most spectra at a full beam (or more) east of the nuclei are basically free from any contribution of the nuclear CO emission. We also notice that, although the difference is small (\( \sim 50 \) km s\(^{-1}\)), the systemic velocity in the overlap region is lower than that of the entire system, while the systemic velocity south of NGC 4039 is higher. This perhaps is reminiscent of the disk rotation of the molecular gas in the more inclined galaxy NGC 4039. Nonetheless, the average velocities of the molecular gas in the nuclear regions of both galaxies are about same as the systemic velocity of the entire system.

The detailed study of the molecular gas distribution and kinematics is difficult, given the limited resolution of the 12 m beam, which will be thoroughly described in the presentation of the BIMA + NRAO 12 m full-synthesis observations, providing a much improved spatial resolution nearly 10 times better. Although the enormous amount of molecular gas in the overlap region must originate from both spiral galaxy progenitors, the kinematics and the proximity of the molecular gas in the overlap, combined with the velocity spread of the molecular gas motion similar to that in the southern galaxy NGC 4039, seem to suggest that the most molecular gas in the overlap could be originated from the southern progenitor. The molecular gas content of the two progenitors might be initially comparable and both were gas rich. However, the VLA H\(\alpha\) observations appear to show that the progenitor of NGC 4039 was gas poor since most of the H\(\alpha\) in this system is currently in the southern tail extending from NGC 4038 (Hibbard et al. 2001, in preparation).

### 3.3.1. CO in the Southern Tidal Dwarf Galaxy

We have also searched for the faint possible CO emission at several positions in the southern tidal dwarf galaxy (Schweizer 1978; Mirabel, Dottori, & Lutz 1992) at the tip of the tidal tail. A possible weak CO detection from the beam at position R.A. = 12h01m26s, decl. = \(-19^\circ\)00\'37.5\" (J2000) appears to be at the \( \sim 4 \sigma \) level (an integration of more than 12 hr; Fig. 5b). An average of the summed spectra of all observations at the five different positions we have searched (accumulated an integration time of more than 27 hr), appears to confirm the weak CO detection at the \( \sim 5 \sigma \) level. All these observed positions are selected to be around the regions of the highest H\(\alpha\) column density, where the VLA H\(\alpha\) observations (Hibbard et al. 2001, in preparation) have revealed some large concentrations of the atomic gas, distributed extendedly around the region of the tidal dwarf galaxy and along the southern tidal tail. The weak CO detections (Fig. 5b) have also shown the same velocity range as the atomic gas velocity spread, revealed from the VLA H\(\alpha\) channel maps, further indicating that the weak CO emission is likely real. Yet the much deeper integration and the more observing positions in this region are still required in order to firmly present the CO detections at the very high significant levels and to possibly obtain a better understanding of the weak CO distribution and kinematics in a tidal dwarf galaxy.

The integrated CO line intensity from the detected position is \( I_{CO} = 0.37 \pm 0.09 \) K km s\(^{-1}\). The average spectrum of the sum from all four other locations (not shown here) appears to give a similar integrated CO line intensity \( I_{CO} = 0.35 \pm 0.12 \) K km s\(^{-1}\), while the average spectrum of all observations gives an integrated CO line intensity \( I_{CO} = 0.35 \pm 0.07 \) K km s\(^{-1}\). Earlier observations by Smith & Higdon (1994) failed to detect any CO emission, but our observations here are much more sensitive. Using the standard CO-to-H\(_2\) conversion factor, we therefore obtain a minimum molecular gas mass for the tidal dwarf galaxy \( \sim 0.61 \times 10^8 \) M\(_\odot\) if only the detected position is considered. It is likely that the weak CO emission exists in other locations in this region and the total molecular gas mass for the entire tidal dwarf galaxy can be a factor of several larger. Indeed, the summed average spectrum of all five position observations seems to suggest a molecular gas mass \( \geq 2 \times 10^8 \) M\(_\odot\). In any event, this molecular gas mass appears to

| Parameter | Value | References |
|-----------|-------|------------|
| \( d_l \) | 20 Mpc | van der Hulst 1979; Mirabel et al. 1998 |
| \( L_{B} \) | \( 2.9 \times 10^{10} \) L\(_\odot\) | From B mag in RC3 |
| \( L_{IR} \) | \( 6.2 \times 10^{10} \) L\(_\odot\) (IRAS) | Soifer et al. 1989; Sanders et al. 2001, in preparation |
| \( L_{IR} \) | \( 8.0 \times 10^{10} \) L\(_\odot\) (KAO) | Bushouse et al. 1998 |
| \( I_{CO} \) | 90.6 K km s\(^{-1}\) (T\(_{b}\)) | This work |
| \( S_{CO} \) | 3172 Jy km s\(^{-1}\) | This work |
| \( L_{CO} \) | \( 0.3 \times 10^{10} \) K km s\(^{-1}\) pc\(^2\) (T\(_{mb}\)) | This work |
| \( M(H_\alpha) \) | 1.5 \( \times 10^{10} \) M\(_\odot\) | This work |
| \( L_{IR}/M(H_\alpha) \) | 4.2 \( L_{CO}/M(H_\alpha) \) | This work |
| \( M(H_\alpha) \) | 0.4 \( \times 10^{10} \) M\(_\odot\) | van der Hulst 1979; Hibbard et al. 2001, in preparation |
| \( M_{dust} \) | \( \sim 10^8 \) M\(_\odot\) | Haas et al. 2000 |
| \( M_{dust}/M_{dust} \) | \( \sim 190 \) | This work |
| \( L_{HCN} \) | \( 0.7 \times 10^8 \) K km s\(^{-1}\) pc\(^2\) (T\(_{mb}\)) | This work |
| \( I_{HCN} \) | 0.02 | This work |
| \( M(H_\alpha)_{\text{dwarf}} \) | \( \geq 2 \times 10^8 \) M\(_\odot\) | This work |
be larger than that of the molecular complexes detected in the M81 group (Brouillet, Henkel, & Baudry 1992; Walter & Heithausen 1999), yet comparable to the molecular gas mass detected in the other two tidal dwarf galaxies (Braine et al. 2000). It is possible that most of the molecular gas might have come directly from the conversion of $\text{H} \, \text{I}$ into $\text{H}_2$. This is similar to the case in the two tidal dwarf galaxies where the molecular gas was detected in regions of the highest $\text{H} \, \text{I}$ concentrations (Braine et al. 2000) and is also related to the case in the cold intragroup medium where huge $\text{H} \, \text{I}$ concentrations and the CO detection are both associated with the intragroup starburst (Gao & Xu 2000) in the famous compact galaxy group Stephan’s Quintet.

3.4. HCN(1–0) Detections and the Dense Molecular Gas

The high dipole-moment molecules like HCN, which traces the dense molecular gas at a density $\gtrsim 10^4 \, \text{cm}^{-3}$, are better tracers of the star-forming gas than that of CO.

**Fig. 4.**—CO integrated intensity maps (contours) in the velocity ranges (a) 1350–1450 km s$^{-1}$, (b) 1450–1550 km s$^{-1}$, (c) 1550–1650 km s$^{-1}$, (d) 1650–1750 km s$^{-1}$, and (e) 1750–1850 km s$^{-1}$ (f) and over the entire velocity range 1300–900 km s$^{-1}$, compared with the underlying optical image (gray scale). All contours plotted in (a)–(e) are 0.4, 0.7 to 2.5 K km s$^{-1}$ in increases of 0.3 K km s$^{-1}$. (f) CO integrated intensity map over the total velocity range (essentially the same as the contour map in Fig. 2, but here all CO data have been used), which has contours 1.4, 2, 3, 4, 6, to 34 K km s$^{-1}$, in increases of 2 K km s$^{-1}$. 
We have detected weak HCN(1–0) emission from two positions, one at the nucleus of NGC 4038 and the other covering both the disk overlap and the nuclear region of NGC 4039 (FWHM ~ 72" at 89 GHz, the two thick circles in Fig. 1). Figure 5c shows the two HCN spectra and the total HCN luminosity can be estimated by the sum of the two beam measurements. This is because in nearby galaxies where HCN maps exist the dense molecular gas tends to be concentrated in the innermost disks of the

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig5a.png}
\caption{(a) The deep CO(1–0) spectra near the southeastern (SE) edge of the overlap region (the SE corner of the merging disks in Fig. 1). The numbers refer to the offsets in arcseconds, with respect to the northern nucleus, and the central position here corresponds to an offset of (110", ~82.5"). (b) Both the summed average spectra (top) from all five positions searched for CO (more than 27 hr integration) in the tidal dwarf galaxy and the deep integration spectrum (bottom) at position of R.A. ~ 12h01m26s, decl. ~ 19°00′37.5″ (J2000) (more than 12 hr integration) show tentative weak detections. (c) HCN(1–0) spectra obtained from the northern galaxy NGC 4038 and from the overlap region plus the southern galaxy NGC 4039.}
\end{figure}
highest density regions (Gao 1996; Helfer & Blitz 1997a). Thus, it is unlikely that any significant HCN emission in Arp 244 still exists outside the coverage of the two HCN beams. We estimated the total HCN flux to be $S_{\text{HCN}} dV = 39 \pm 6\, \text{Jy km s}^{-1}$ ($I_{\text{HCN}} = 1.2 \pm 0.2\, \text{K km s}^{-1}$, using a $\sim 32\, \text{Jy K}^{-1}$ conversion) and the HCN luminosity to be $L_{\text{HCN}} = 0.7 \times 10^8\, \text{K km s}^{-1}\, \text{pc}^2$. Therefore, the luminosity ratio of $L_{\text{HCN}}/L_{\text{CO}} = 0.02$ implies that only $\gtrsim 4\%$ of the molecular gas is at a high density of $\gtrsim 10^4\, \text{cm}^{-3}$ in Arp 244 (Gao 1996; Gao & Solomon 2000a). This is surprisingly low since ULIGs can have $L_{\text{HCN}}/L_{\text{CO}}$ as high as 0.25 and up to about half of the molecular gas at density $\gtrsim 10^4\, \text{cm}^{-3}$ (Solomon et al. 1992; Gao 1996; Gao & Solomon 2000a). The ratio of $L_{\text{HCN}}/L_{\text{CO}}$ in Arp 244 is actually just comparable to that of the Milky Way disk (Helfer & Blitz 1997b), even lower than that of some “normal” spiral galaxies (Gao & Solomon 2000a). The fraction of the dense molecular gas in Arp 244 is apparently the lowest among all LIGs observed so far.

Although most of the CO emission ($\gtrsim 60\%$) is from the overlap region, the HCN emission in the overlap appears to be less than half since only about half of the HCN emission is originated from both NGC 4039 and the overlap. The HCN detection from the overlap region and NGC 4039 has only a comparable integrated line intensity, but it is weaker in the antenna temperature as compared with the detection in NGC 4038. The two HCN spectra differ clearly in the velocity spread: a narrow velocity space in the HCN emission of NGC 4038 but a much broader velocity spread in NGC 4039 and the overlap region. Thus, the HCN spectra basically indicate that the dense molecular gas could have gas kinematics similar to that of the total molecular gas revealed from the CO emission, even though their spatial distributions are probably totally different.

The low fraction of the dense molecular gas in Arp 244, especially in the overlap region, is consistent with the fact that the bulk of the molecular gas in the overlap is extensively distributed both spatially and kinematically (Figs. 2, 3, and 4). Although there are several CO peaks in the high-resolution synthesis maps, none of them has the extremely high concentrations of molecular gas that are found in ULIGs. The highest gas surface density in the northern nucleus is $\approx 2.5 \times 10^3\, M_\odot\, \text{pc}^{-2}$ (resolved on a linear scale of $\sim 0.5\, \text{kpc}$ as in both the BIMA + NRAO 12 m and the new OVRO CO maps), an order of magnitude smaller than those in ULIGs, while the gas surface density in the southern nuclear region is lower by at least a factor of 3 and comparable to that of the CO peaks in the overlap. Our low-resolution ($55'' \sim 5\, \text{kpc}$) 12 m map reveals a CO peak in the disk overlap region since most of the molecular gas is concentrated there. The peak molecular gas column density
**Fig. 6.**—The 20 cm radio continuum to CO(1−0) emission ratio map (contours) compared with the HST/WFPC2 image (gray scale). This illustrates the sites of the most intense starbursts of the highest star formation efficiency (SFE). White contours indicate the sites of the highest ratios, ~5 times above the average, suggesting the highest SFE $\gtrsim 20 \ L_\odot/\ M_\odot$. Black contours are the sites of a factor of 2 lower in the radio-to-CO ratios, implying an SFE $\lesssim 10 \ L_\odot/\ M_\odot$.

$N(\text{H}_2)$ is close to $10^{22}$ cm$^{-2}$, i.e., an average gas surface density (over ~5 kpc scale) of about $190 \ M_\odot$ pc$^{-2}$. This low gas surface density together with the low HCN-to-CO line luminosity ratio clearly marks the unique gas properties in Arp 244, in sharp contrast with those in most LIGs/ULIGs.

### 3.5. Local Star Formation Efficiency and the Radio-to-CO Ratio Map

There is apparently a correlation between the radio continuum and the CO emission as indicated even in the old OVRO CO map (Hummel & van der Hulst 1986; Stanford et al. 1990). Particularly, most of the radio continuum emission is concentrated in the overlap region with a very similar morphology to that of the CO. The direct comparison of the KAO 60 $\mu$m maps (Evans, Surace, & Mazzarella 1997) with our full-synthesis CO images clearly reveals that the average FIR-to-CO ratio in the overlap region is higher than the global ratio since most of the FIR emission ($\gtrsim 75\%$) is from the overlap region, while only $\gtrsim 60\%$ CO emission is from the same region. Therefore, the average SFE in the overlap can be a bit higher than the global value [which is $L_{\text{IR}}/N(\text{H}_2) = 4.2 \ L_\odot/\ M_\odot$, or $5.3 \ L_\odot/\ M_\odot$ if a higher 100 $\mu$m KAO flux of Bushouse et al. (1998) is used], still comparable to that of GMCs in the Galactic disk and an order of magnitude lower than that of ULIGs (Sanders & Mirabel 1996; Solomon et al. 1997). On the other hand, the average SFE in the nuclear regions is expected to be lower than the global value since the two nuclear regions have extremely weak FIR emission, while the CO is highly concentrated, particularly in NGC 4038. Moreover, the radio continuum emission has indeed an excellent correspondence with the FIR maps, just as expected from the
The overall ratio map (contours) of the 20 cm radio continuum to the CO emission compared with the VLA 20 cm radio continuum image (gray scale). Here black contours are the sites of the highest radio-to-CO ratios (same as the white contours in Fig. 6) and the ratios a factor of 1.5 lower, gray contours are for the radio-to-CO ratios a factor of 2 lower than the highest (same as the black contours in Fig. 6) and those a factor of 1.5 further lower, and white contours are for the lowest radio-to-CO ratios, a factor of 4 and 6 lower than the highest, indicating the sites of SFE L_*/M_\odot and lower, about the average SFE across over the entire system.

In order to further quantify the local star formation properties and better identify the sites of the most intense starbursts with the highest SFE, we have produced the ratio map of the VLA 20 cm radio continuum to the CO(1–0) emission. Since the tight FIR/radio correlation is also valid on a kiloparsec scale in galaxies (e.g., Marsh & Helou 1995; Lu et al. 1996), the radio continuum emission can be used as a tracer of the recent star formation in galaxies as well (e.g., Condon et al. 1990, 1991; Condon 1992). Here we use the radio continuum maps to roughly indicate the star formation sites. Thus, a high-resolution indicator of the FIR emission can be inferred by scaling the FIR according to the radio continuum emission. Comparing the radio continuum maps with the detailed molecular gas distribution from the CO imaging, we can obtain the radio-to-CO ratio map to reveal the local SFE, which is defined as the local ratio of the star formation rate to the molecular gas mass. Both the VLA 20 cm continuum and the BIMA + NRAO 12 m full-synthesis CO maps have about same resolution, thus a direct division can be performed to obtain the ratio map.

The radio continuum to the CO ratios has been plotted as contours and compared with the HST/WFPC2 (Fig. 6) and the VLA radio continuum images (Fig. 7). Apparently, a rather smooth distribution of the radio-to-CO ratio is observed across most of the merging disks. The sites of the highest ratios, ~2.5 and 5 times above the average, have been indicated in Figure 6 as black and white contours, respectively, and they coincide well with the dusty patches across the HST/WFPC2 image. The sites of the highest
radio-to-CO ratios are exclusively localized in the most prominent dusty regions in the overlap, which are near the CO peaks and probably the FIR emission peaks. The correspondent highest SFE is therefore $\gtrsim 20 \frac{L_\odot}{M_\odot}$ since the global average SFE is $4.2 \frac{L_\odot}{M_\odot}$. Interestingly, almost all LIGs/ULIGs have SFE $\gtrsim 20 \frac{L_\odot}{M_\odot}$ (Sanders & Mirabel 1996), although some early-stage premerging LIGs with SFE $\sim 10 \frac{L_\odot}{M_\odot}$ and lower do exist (e.g., Arp 302; Lo, Gao, & Gruendl 1997).

Consistent with what can be roughly expected from a direct comparison of the FIR map at 60 $\mu$m with the CO images in the nuclear regions, both nuclei have only a low radio-to-CO ratio, about the average or lower (Fig. 7). Thus the SFE in the nuclear regions is about $4 \frac{L_\odot}{M_\odot}$. The ISO MIR “hotspots” have higher ratios than the average, and so do the extended overlap region and the western star-forming loop in NGC 4038, in addition to a few spots around the nuclear regions (especially the circumnuclear region of NGC 4038; Fig. 6). But these are a factor of 2 lower than the highest ratios and are only of moderate starburst sites with an SFE $\gtrsim 10 \frac{L_\odot}{M_\odot}$, which is actually the typical SFE value for the local starburst galaxies (Sanders & Mirabel 1996).

4. DISCUSSION

Both observational and theoretical studies have demonstrated that the ultraluminous extreme starburst phase is most likely achieved in the molecular gas-rich mergers (e.g., Sanders & Mirabel 1996; Mihos & Hernquist 1996; Downes & Solomon 1998; Gao & Solomon 1999), where starbursts may proceed through the formation of numerous super–star clusters (e.g., Whitmore et al. 1999; Surace et al. 1998; Scoville et al. 2000). Multiwavelength observations of Arp 244 and comparison with the early-stage mergers observed by Gao et al. (1999) are therefore especially crucial to track how and when the dominant sources of star formation transform from within the disks of the two gas-rich spirals to the disk-disk overlap regions between the two galaxies. Moreover, comparative studies with CO observations of the late-stage mergers (Downes & Solomon 1998; Bryant & Scoville 1999) are also equally important for understanding how starbursts continue to evolve from taking place predominantly in the overlap regions to occurring mainly in nuclear regions when the merging advances to ULIG phase, with extraordinary nuclear concentrations of dense gas. Intermediate mergers like Arp 244 appear apparently as an important link in the merging process between a pair of gas-rich premergers and the merged double-nucleus ULIG. We here discuss only the starburst properties of Arp 244 related to our 12 m observations.

4.1. Ultraluminous Extreme Starburst Potential

The CO content decreases as merging progresses, indicating the depletion of molecular gas due to merger-induced starburst (Gao & Solomon 1999). Using the scaling of $M(H_\text{2}) \sim S_{\text{CO}}^{8/3}$ (Gao & Solomon 1999, valid for mergers at the early and intermediate stages, with the projected nuclear separation $20 \gtrsim S_{\text{sep}} \gtrsim 2$ kpc), the total molecular gas will decrease roughly by more than a factor of 2 when Arp 244 reaches $S_{\text{sep}} \sim 2$ kpc, prior to or at about the time it enters the late merging stage. It appears that all ULIGs observed so far have $\sim 10^{10} M_\odot$ of molecular gas mass or more without exception, even after considering up to a factor of 5 reduced CO-to-H$_2$ conversion (Solomon et al. 1997). The ultraluminous starburst phase of Arp 244 is thus possibly reachable in the advanced stage since only $\sim 10^{10} M_\odot$ molecular gas will be consumed by the newborn stars in the next $\sim 10^8$ yr of the merging process. There will still be abundant molecular gas of close to $\sim 10^{10} M_\odot$ available, not to mention the additional amount of atomic gas in the merging disks and in the long tidal tails (Hibbard et al. 2001, in preparation) that may eventually fall back to the merging disks (Hibbard et al. 1994). The atomic gas could be an additional gas reservoir for possible conversion into the molecular phase, because there appears to be some evidence that ULIGs tend to have the highest ratio of $M(H_\text{2})/M(H_\text{i})$ (e.g., Mirabel & Sanders 1988, 1989).

In general, the gas surface density increases from orders of a few times $10^2 M_\odot$ pc$^{-2}$ to a few times $10^3 M_\odot$ pc$^{-2}$ as merging progresses from early to intermediate stages (Gao et al. 1999) (unresolved on a scale of 1–2 kpc), while advanced ULIG mergers such as Arp 220 have gas surface densities typically greater than $10^4 M_\odot$ pc$^{-2}$ (Scoville et al. 1997; Downes & Solomon 1998; Sakamoto et al. 1999). Although the total molecular gas content of Arp 244 is comparable to that of ULIGs, the gas surface densities is still orders of magnitude lower than that of ULIGs, e.g., in the overlap, $\sim 10^2 M_\odot$ pc$^{-2}$ on a scale of 5 kpc and $\sim 10^3 M_\odot$ pc$^{-2}$ on a resolved scale of subkiloparsec. Therefore, only a small fraction of the molecular gas in Arp 244 is actually at a high enough gas surface density for a high SFE, as formulated in the Schmidt law (e.g., Kennicutt 1998). The overall gas density is low to maintain a low SFE across the entire system, except for some localized starburst regions (Fig. 6), just as our HCN observations have revealed that there is little dense molecular gas available currently to power the extreme starbursts.

Ultraluminous extreme starbursts require not only a large quantity of molecular gas but also a high gas concentration, particularly nuclear gas concentration, so that the bulk of the molecular gas is at a high density. The large quantity of preexisting molecular ISM is sufficient fuel for Arp 244 to ultimately reach the onset of the ultraluminous starburst phase, as the merging proceeds to the advanced stage and the bulk of the molecular gas becomes highly condensed. Unlike most LIGs/ULIGs, which show the dominant nuclear MIR and perhaps FIR emission (Hwang et al. 1999; Soifer et al. 2000; Bushouse et al. 1998; Xu et al. 2000), Arp 244 has only moderate nuclear emission in MIR (Mirabel et al. 1998; Xu et al. 2000), and the KAO 60 $\mu$m emission from the two nuclei is extremely weak (Evans et al. 1997). Although there is no clear indication of a large stellar bulge in either of the galaxies, the concentrations of the molecular gas as well as the stars in the nuclear regions in Arp 244 perhaps also draw some analogies to the case of a galaxy-galaxy merger model with stellar bulges in the progenitors (Mihos & Hernquist 1996). In reality, Arp 244 is probably more in between the two extreme cases modeled by Mihos & Hernquist (1996). According to the models (see Fig. 5 in Mihos & Hernquist 1996), the first peak of starburst phase has recently passed in Arp 244, shortly after the pair’s first closest approach, perhaps as evidenced by numerous young star clusters in the HST/WFPC2 images. Thus, Arp 244 could have just phased out the bona-fide starburst LIG stage. As more and more gas continues to accumulate in both the overlap and the two nuclear regions, the further nuclear gas concentrations and the continuous
star formation can build stronger bulges that can help stabilize the disks against the bar formation, lower the SFE levels during the merging, and leave enough gas for the strongest final starburst when the two galaxies eventually coalesce, with almost all the molecular gas collapsed into a kiloparsec double-nucleus region. More than an order of magnitude increase in the SFE, combined with an abundant molecular gas supply of \( \sim 10^{12} \, M_\odot \), will be just sufficient to make Arp 244 into \( L_\text{irk} \sim 10^{12} \, L_\odot \). Interestingly, there also appears to be some quite widely separated ULIGs (\( S_{\text{sep}} > 10 \) kpc), which might still be in their early stage of merging, but may have passed their first closest impacts, and might have just been experiencing their first strongest starbursts (Murphy 2000).

In summary, a preexisting abundant molecular gas content is a necessary for there to be a possibility of a merging spiral pair reaching the ultraluminous starburst phase. Arp 244, with a large quantity of molecular gas available at low density, a low SFE, a moderate FIR luminosity or star formation rate, and yet a relatively early/intermediate stage of merging, has the potential of producing an ultraluminous extreme starburst in late stage of merging, when the molecular gas complexes in the overlap region eventually merge with the nuclear gas concentrations and finally collapse into a kiloparsec-scale double-nucleus gas disk.

4.2. Starbursts and Current Intense Star Formation Sites

The well-known correlation between the FIR thermal dust emission and the radio continuum synchrotron emission, unexpected, as they are apparently two unrelated physical mechanisms, is probably the tightest relation known among the global quantities of galaxies (e.g., Helou et al. 1985; Condon 1992; Xu et al. 1994). The morphologies of the two emissions are also similar, and the correlation between them appears to hold down to a kiloparsec scale within individual galaxies (e.g., Bica, Helou, & Condon 1989; Marsh & Helou 1995; Lu et al. 1996). Based on these, we approximately scaled the local FIR emission according to the radio continuum emission and compared it with the molecular gas distribution to measure the local SFE. We have clearly identified that the most intense bursts of star formation (the sites of the highest SFE, i.e., the highest radio-to-CO ratios; Fig. 6), currently being observed, are not in the concentrations of the optically revealed star cluster concentrations, or even the peaks of the MIR emission, nor necessarily at the exact locations of the CO and 20 cm radio continuum emission peaks. Instead, the strongest starbursts appear to be confined in small regions near the CO, radio continuum, and FIR emission peaks in the overlap region. The bulk of the molecular gas across over the entire system is making stars with a rather modest or "normal" SFE (Fig. 7).

Let us emphasize what we have learned from our observations and the various other observations. Starbursts have apparently been going on or have happened in some regions in Arp 244 as evidenced by super-star clusters (Whitmore et al. 1999) and the MIR "hotspots" in the overlap (Mirabel et al. 1998). Yet most of the FIR emission (as well as the MIR), which dominates the total energy output, comes from the overlap region (Evans et al. 1997; Bushouse et al. 1998), where most molecular gas resides, rather than from the super-star cluster concentrations. Although Arp 244 has long been claimed as the nearest archetypal starburst merger, our observations show that the molecular gas is rather extensively distributed over the entire merging disks, although most is still in the overlap, and the bulk of the molecular gas is only making stars at a low SFE. The entire system is presently not undergoing a global burst of star formation, even though some localized starbursts are occurring in the overlap, and a global starburst could have just peaked recently, right after the first closest impact responsible for the formation of the tidal tails.

Whitmore et al. (1999) found that the star clusters at the edge of the dusty overlap region appear to be the youngest, with ages \( \leq 5 \) Myr, while the star clusters in the western loop in NGC 4038 appear to be \( 5-10 \) Myr old. Indeed, these are the sites of the most intense and moderate starbursts, respectively, as revealed by the radio-to-CO ratio map in Figure 6. There might be many youngest star clusters totally obscured by the dust at the most intense starburst sites, contributing significantly to the dominant energy output in the overlap region. On the other hand, many star clusters in the northeastern region that appear to be \( \sim 100 \) Myr old, and even older star clusters across over the system, are not the current starburst sites, contributing little to the total FIR emission. These old star clusters are probably related to the recent large-scale active star formation that happened after the first closest encounter.

The excellent agreement among the FIR-to-CO ratios, the dark patches in the HST/WFPC2 images, and the youngest ages of the star clusters, are striking. Apparently, both the most intense localized starbursts and the overall large-scale star formation are occurring in the overlap region, where all the CO, \([C\, II]\) line (Nikola et al. 1998), FIR, and radio continuum show high concentrations. But the confined intense starburst sites, which are heavily obscured in the dust, have SFE only \( \geq 20 \, L_\odot/ M_\odot \) just reaching the typical SFE level for LIGs/ULIGs. On the other hand, the average SFE in the overlap is just slightly larger than \( 4 \, L_\odot/M_\odot \), still comparable to that of the Galactic disk GMCs.

One caveat is that Arp 244 may be twice luminous in 100 \( \mu m \), as measured by the KAO (compared with that of the IRAS measurement, Bushouse et al. 1998), although the 60 \( \mu m \) measurements agree (Evans et al. 1997). This discrepancy needs future FIR observations to resolve. More importantly, it is perfectly possible that the standard CO-to-H\(_2\) conversion factor can be an overestimate for the total molecular gas mass. Therefore, it is likely that the global SFE in Arp 244 can be up to more than a factor of 2 larger than that of the GMCs in the Milky Way disk. This may indeed suggest that an enhanced global SFE proceeds throughout the entire merging disks while some confined strongest starbursts have a highest SFE much larger than \( 20 \, L_\odot/M_\odot \), typical for ULIGs. In any case, the highest radio-to-CO ratio sites could actually be bona fide sites of the current starbursts with an elevated SFE and may contribute a significant fraction to the total FIR emission, even though most of the FIR emission may still come from the regions of a normal or modest SFE.

Using the \([C\, II]/CO(1-0)\) line ratio to distinguish between starburst activity in galaxies and more quiescent regions (Stacey et al. 1991), Nikola et al. (1998) concluded that there is no strong starburst activity taking place in Arp 244 on a scale of \( \sim 5 \) kpc, the resolution of their data. This is roughly in agreement with our results since starburst sites are identified only on a scale of \( \leq 1 \) kpc (Fig. 6). Nikola et al. (1998) further argued that most of the \([C\, II]\) emission might...
have come from the confined active star-forming regions surrounded by the more quiescent GMCs. Our results appear to support this claim if indeed the sites of the intense starbursts, which are identified from the high radio-to-CO ratios (Fig. 6), produce the bulk of the [C II] emission. Additional supports for the confined starbursts in small regions in the overlap are the recent ISO-SWS measurements (Kunze et al. 1996) and the ISO-LWS observations, including the detection of Brγ knots in the overlap interaction zone (Fischer et al. 1996).

The rather extended moderate starbursts also coexist closely with the confined, most intense starbursts in the overlap region. Other interesting sites of moderate starbursts are the western loop/ring structure and part of the \( \gtrsim \) kiloparsec scale circumnuclear regions (mainly in NGC 4038), but not the nuclei themselves (Figs. 6 and 7), with nearly 3 times higher SFE than the average. The western loop coincides with the molecular ring we have mapped from the BIMA + NRAO 12 m full-synthesis CO image, which was completely absent from the old OVRO CO map (Stanford et al. 1990) and was only partially revealed in the new OVRO CO map (Wilson et al. 2000). It appears that the starbursts occur at a moderate level in the southeast side of the overlap region, proceed progressively with increased intensity northwesterly across the overlapping molecular concentrations, and produce the most vigorous starbursts in the northern and western edges of the huge molecular gas agglomerations in the overlap interaction zone (Fig. 7).

Moderate [C II] emission is also detected in the western loop (Nikola et al. 1998), which also indicates the moderate star-forming activity there. This is again consistent with our results obtained from the radio-to-CO ratios. Moreover, the [C II] emission peak appears to be slightly offset from our single-dish CO peak (Figs. 2 and 4/7), which is resolved into several CO peaks by the interferometers. The strongest [C II] emission seems to be roughly coincident with the sites of the highest SFE, just north of the CO peak in the NRAO 12 m map. Our single-dish CO map also appears to be roughly peaked at same position as that of the KAO 60 (Evans et al. 1997), 100, and 160 \( \mu m \) maps (Bushouse et al. 1998). The strongest MIR peak in the overlap region that is inconspicuous at optical wavelength (Mirabel et al. 1998; Xu et al. 2000), however, may correspond only to the southernmost CO peak in the overlap (Wilson et al. 2000), which is not one of the strongest starburst sites and has only a moderate SFE \( \gtrsim 10 L_\odot/M_\odot \) (Figs. 6 and 7). Therefore, the strongest peaks of the CO, radio continuum, and FIR, as well as the MIR peaks, are not necessarily the exact sites of the highest SFE, or the most intense starbursts. The highest radio-to-CO ratio peaks, which may reveal the sites of the most vigorous star formation with the highest SFE, and the strongest [C II] emission peaks, which arise mainly from the photodissociation regions, appear to be the best probes of the most intense starbursts, which might be totally obscured in the optical/near-IR and even MIR regime.

4.3. Star Formation from the Multiwavelength Observations

In light of the numerical models for mergers of Arp 244 (Toomre & Toomre 1972; Barnes 1988; Mihos et al. 1993; Mihos & Hernquist 1996; Barnes & Hernquist 1996, 1998) and the multiwavelength observations of Arp 244, comparison of the various observations and statistical studies of LIG mergers with those models can be fruitful. We here try to discuss qualitatively the onset of the starbursts, the fate of the starbursts, and the possible ultraluminous extreme starburst phase in Arp 244, utilizing these observational and theoretical results.

**ROSAT** high-resolution imager (HRI) X-ray map (Fabbiano et al. 1997) and the high-resolution and high-sensitivity Chandra X-ray images from the Chandra news release (Fabbiano et al. 2000), after the submission of this paper show some correspondence with the discrete radio knots. Most soft X-ray emission, however, is from the disks and nuclear regions, rather than from the overlap region, even though several X-ray emission knots exist in the overlap. Yet, more soft X-ray structures in regions of the ISO “hotspots” are evidently better revealed in the new Chandra X-ray images. Both the X-ray and radio continuum show extended morphology (prominent ring structure) in the northern galaxy NGC 4038, although not in NGC 4039. Since supernova remnants are most likely responsible for the majority of both extended emissions, these observations may be used as probes to identify past active star formation sites. According to the various models, the first burst of star formation may have occurred several \( \sim 10^8 \) yr ago when the first closest approach of the galaxy pair happened. Many X-ray knots with the radio emission correspondence can be even older, and they are reminiscent of the possible star-forming sites in the past, prior to or during the first strongest impact. Overall, these emissions could mark roughly the sites of the interaction-enhanced large-scale star formation across the pair’s disks at the earliest stage of merging.

H\( \alpha \) emission and young star clusters shown in the HST images (Whitmore et al. 1999) indicate that recent vigorous star formation is also proceeding throughout the entire merging disks. Molecular gas concentrations in the overlap may have hidden some extremely young star clusters and H\( \alpha \) regions. Nevertheless, these again are the rather recent large-scale bursts of star formation occurring probably right after the genesis of the tidal tails, after the pair’s first closest approach.

Both the MIR and FIR observations (Mirabel et al. 1998; Xu et al. 2000; Evans et al. 1997; Bushouse et al. 1998) show the strongest peaks in the rather extended overlap region where the bulk of the molecular gas resides. But the MIR and FIR emission peaks differ from each other, while the FIR peaks roughly at same position as that of the CO. Generally speaking, the overlap region is the current site of vigorous star formation or starburst. Yet the overall starburst level is at modest. The strongest starburst sites with SFE comparable to that of LIGs/ULIGs are confined to \( \lesssim \) kiloparsec-scale small regions in the overlap, and the global SFE level is about same as those in the Milky Way disk GMCs. Despite the fact that some localized starbursts are still going on, the recent peak of the starburst phase in Arp 244 has most likely passed already, and the entire system is currently in a rather quiescent star formation phase.

The radio continuum-to-CO ratio map implies low SFE at both nuclei (Fig. 7). The highest gas concentration in Arp 244 revealed by the interferometers is, however, in the northern nuclear region, which has only a moderate \( \gtrsim \) kiloparsec-scale circumnuclear starburst ring, rather than a subkiloparsec nuclear starburst. The highest radio-to-CO ratios are the confined bona fide starburst sites (Fig. 6), which appear to have some correspondence with the [C II]...
emission peaks (Nikola et al. 1998). The CO emission peaks in the overlap region appear not to be at the exact locations of the localized starbursts, and the most intense starbursts might not be at an extremely high SFE level as in ULIGs. These highest molecular gas concentrations are likely to undergo future ultraluminous extreme starbursts once they all merge together with the nuclear gas concentrations, and collapse into ~ kiloparsec scale in the final coalescence. Although the progenitor galaxies of Arp 244 could only have small stellar bulges, the bulges can be built up through merging (e.g., Carlberg 2000) in addition to nuclear gas infalls and concentrations. Thus, Arp 244 fits most likely between the two extremes modeled by Mihos & Hernquist (1996), and more than an order of magnitude enhanced SFE can be achieved in the final merging.

Although most (≥ 60%) H I gas is distributed in the tidal tails (van der Hulst 1979; Hibbard et al. 2001, in preparation), there are still ~2 × 10^8 M⊙ H I in the merging disks, while most ULIGs have little H I left in the merged disks (Hibbard & Yun 1996, 2000; Mirabel & Sanders 1988, 1989). Most H I in Arp 244 is in the southern tail, where we tentatively detected CO emission at the tip of the tidal tail, indicating a molecular gas mass of ≥ 2 × 10^8 M⊙ in the tidal dwarf galaxy. These are additional gas reservoirs for future star formation, especially when the extraordinary H I tails rain back onto the merging disks (Hibbard et al. 1994), converting most H I gas into molecular phase.

Our recent H I observations of NGC 6670 suggest that a precursor to Arp 244 can be that the H I disks have merged into a huge overlap concentration in the extended H I disks, prior to the merging of the stellar and molecular gas disks (Wang et al. 2000). In Arp 244, although an anticorrelation between the molecular and atomic gas distributions appears to exist, there is still a significant amount of H I gas in the molecular gas overlap region. Whether there was an H I gas overlap formed previously, prior to the merging of the molecular gas disks, requires high-resolution H I observations and further comparative studies of the multi-wavelength observations, in combination with the numerical modelings, to test. Clearly, understanding of the formation and evolution of the overlap region is the key to ultimately comprehending the entire star formation history of Arp 244.

4.4. Overlap Star Formation and Starburst Mechanisms

The formation of the overlap star formation regions, unnecessarily as overwhelmingly dominant as in the case of Arp 244, might be a quite common phenomenon in merging galaxies (Xu et al. 2000). Both the simulations and observations have shown that the gas is being transported into the nuclear regions when a pair of spiral galaxies undergoes the merging process, in addition to being dragged out into the tidal tails (e.g., Olson & Kwan 1990a, 1990b; Nozouchi 1991; Mihos & Hernquist 1996; Barnes & Hernquist 1991, 1996; Scoville et al. 1991; Gao et al. 1999; Hibbard & van Gorkom 1996). Yet, models appear to be unable to reveal the early formation of the gas concentration in the overlap region when galaxies are still quite widely separated, like the intermediate merger Arp 244 with the molecular gas overlap, where most gas resides, and the early merger NGC 6670 with the atomic gas overlap. Could a significant amount of the atomic gas, especially in the southern progenitor, have ended up in the overlap region in the first place, prior to the formation of the molecular gas overlap, more as a result of efficient H I cloud-cloud collisions than of the collisions of the GMCs, when the two gas-rich spiral progenitors first collided? This is because the mean free path of an H I cloud is ~ 33 pc, much smaller than the size of the overlap region, yet the GMCs’ mean free path is orders of magnitude larger and the chance of GMC collisions in the overlap is extremely small (Jog & Solomon 1992). Just like the early merger NGC 6670, which has the H I gas concentration in the H I disk overlap region formed prior to the merging of the stellar and molecular gas disks (Wang et al. 2000), there might be a similar H I gas overlap formed in Arp 244 during its earliest merging stage.

Jog & Solomon (1992) argued that a starburst occurs when the preexisting GMCs in the overlap region undergo radiative shock compressions by the preexisting high pressure of the central molecular intercloud medium produced by the heating from the H I cloud-cloud collisions. If indeed an H I disk–disk overlap region could be formed prior to the merging of the stellar and molecular gas disks, the dominant star formation should not be occurring in the H I gas overlap region, given that few GMCs exist in this H I cloud-cloud collision ISM during the early stage of merging. Instead, large-scale star formation and nuclear starbursts induced by the gas inflow are probably at play (Combes et al. 1994). It is later formation of the molecular gas disk overlap, within this preexisting high-pressure overlapping H I gas concentration, when the merging advances into the intermediate stage, that will probably make GMCs in the overlap undergo starburst by the radiative shock compressions (Jog & Solomon 1992).

Although the soft X-ray emission in the overlap region in Arp 244 is neither strong nor extended, as revealed by the ROSAT HRI (Fabbiano et al. 1997), this may be due to the high gas column density in the overlap, which absorbs the most extended soft X-ray emission. The Chandra soft X-ray images of much improved sensitivity and resolution do show some extended features in the overlap, which are in particularly good correspondence with the MIR “hotspots.” This is on the right track, just as expected from the prediction of the overlap starburst model of Jog & Solomon (1992). Higher energy X-ray imaging that can penetrate through the heavy dust/gas concentration in the overlap, yet still orders of magnitude below the Compton-thick limit, and the extinction-corrected soft X-ray images of Arp 244 could be the key to further test the overlap overpressure starburst mechanism.

In advance mergers, the double-nucleus gas disks are already merging with the overlap gas concentrations, with most gas either between (e.g., NGC 6240; Tacconi et al. 1999) or around the double-nucleus (e.g., Arp 220, Downes & Solomon 1998; Sakamoto et al. 1999) in ~ kiloparsec scale, in addition to the nuclear gas concentrations. Thus, a possible merging sequence for a gas-rich pair of spirals may look like the following: from the build-up of the H I gas disk overlap regions (NGC 6670) → the sufficient overlap in both stellar and molecular disks (Arp 244) → the kiloparsec-scale merging double nucleus gas disks, either with a central gas concentration between the nuclei (NGC 6240) or with an extended gas disk of several kiloparsec surrounding the nuclei (Arp 220). The transformation of the merging phases and the further development of the overlap regions are also accompanied by the change in the dominant sources of the total power output: from large-scale star
formation within galaxy disks in early mergers → the mainly localized starbursting overlap regions between the galaxies in intermediate mergers → the extreme starburst in the highly concentrated double-nucleus subkiloparsec sources in advanced ULIGs.

The overpressure starburst mechanism (Jog & Solomon 1992) is probably happening in intermediate mergers, especially those with the extensive overlap regions like Arp 244. Yet, this mechanism appears to require a sufficient overlap between the gas disks so that the early formation of the gas overlap region is possible. Is this the sole starburst mechanism during the entire merging process when two gas-rich spiral galaxies merge? It is likely that different starburst mechanisms play various roles during different merging stages along a merger sequence. What then are the other triggering mechanisms for the starbursts? Wilson et al. (2000) compared their new OVRO CO map with the ISO MIR emission and suggested that molecular cloud collisions may play an important role for the local intense starburst and the strong MIR emission. Yet Lo et al. (2000) found no obvious signatures of cloud collisions from analyzing the molecular gas kinematics in the BIMA + NRAO 12 m full-synthesis CO data. Perhaps Arp 244 is on its way to changing from the overpressure overlap starburst to the direct cloud-cloud collision starburst.

An extensive active star-forming molecular gas overlap region observed in Arp 244 may not always be the case for most mergers. In fact, most LIgs do not show such an extensive molecular gas overlap region (e.g., Gao et al. 1997, 1999; Bryant & Scoville 1999). Even though star formation in the overlap can be common in mergers, the overlap starburst is probably much less dramatic than that of Arp 244 in most cases (e.g., Xu et al. 2000). But do all gas-rich mergers develop such an extensive molecular gas overlap phase during the course of merging? We do not have a definite answer. Only in late merging stage have both observations and numerical simulations demonstrated the existence of the highly concentrated molecular gas between the merging nuclei. Also, only in advanced mergers can the chance of GMC-GMC collisions be much enhanced since almost all the molecular gas (in both the overlap and the two nuclear gas concentrations) finally condenses into a kiloparsec scale. Now the mean free path of GMCs is less than the size scale of the gas concentration region since the volume filling factor of GMCs is increased tenfold, making even the intercloud medium molecular. Therefore, direct collisions of GMCs could be playing an important role for the enhanced starburst when merging progresses into advanced stage in the final coalescence.

5. CONCLUSIONS

We summarize our main results and present our concluding remarks in the following:

1. Our fully sampled CO(1–0) map (FWHM ~ 55") at half-beam spacing reveals a factor of 5.7 larger total CO flux in Arp 244 than was previously accepted. This is mainly due to the enormous CO extent of Arp 244, which is much larger than the single pointing 55" beam used in the old observation. In general, single-beam observations of merging systems may well systematically underestimate CO content in the cases where the merging systems are much larger than the single beam, unless a map of extensive coverage of the merging systems is made. Most of CO emission in Arp 244 indeed peaks at the disk overlapping region with a broad velocity spread of 600 km s⁻¹. We obtain a total molecular gas mass of 1.5 × 10¹⁰ M☉ for Arp 244 using a standard CO-to-H₂ conversion factor.

2. HCN(1–0) emission has been detected in Arp 244. HCN observations suggest that there is only a small amount of dense molecular gas in Arp 244 compared with the total molecular gas content. The fraction of the dense molecular gas is only comparable to that of normal spiral galaxies and is much lower than that of LIGs and ULIGs.

3. We detected extended CO emission far away (nearly two full beams) from the major CO concentrations, such as those revealed by the interferometers. The peak CO emission in the overlap region has an average gas surface density near ~ 200 M☉ pc⁻² over ~ 5 kpc—the scale probed by the 55" beam. Even the resolved interferometry CO images only reveal that the highest gas surface density is about 10³ M☉ pc⁻², still an order of magnitude lower than that of ULIGs. This is consistent with the small fraction of dense gas found from the HCN measurements. Weak CO emission from the tidal dwarf galaxy at the tip of the southern tail has also been tentatively detected, and the estimated molecular gas mass is possibly larger than ~ 2 × 10⁸ M☉.

4. The excellent correspondence of the radio continuum images with the FIR maps is evident in Arp 244, which also implies the tight correlation between the two emissions. We use the high-resolution VLA 20 cm image to approximately represent the FIR emission distribution in Arp 244 and compare with the CO images of comparable resolution to estimate the local SFE, which is defined as the FIR to molecular gas mass ratio and is now indicated by the radio-to-CO ratio. SFE is low throughout the entire system with a global SFE = 4.2 L☉/M☉, just the same as that of the Galactic disk GMCs. Only some confined regions in the overlap, inconspicuous in optical observations, are the sites of the current powerful starbursts with SFE ≳ 20 L☉/M☉, comparable to that of LIGs/ULIGs. The VLA radio continuum images also reveal a very similar morphology as that of the molecular gas distribution.

5. Although some localized starbursts are going on in the confined regions in the overlap, the bulk of the molecular gas is forming into stars with a low SFE, just the same as that of normal spiral galaxies. The large amount of total molecular gas, yet only a small amount of dense molecular gas and a low SFE, revealed from our observations, combined with the theoretical predictions of models of gas-rich mergers, seems to suggest that Arp 244 has ultraluminous extreme starburst potential when merging proceeds into late stage. Arp 244 appears to be a snapshot of an ULIG in its early stage of making.

6. Multiwavelength comparison together with numerical models appear to indicate that Arp 244 has recently passed the peak of large-scale active star formation. Globally, the bulk of the molecular gas in Arp 244 is currently not in a starburst phase. The confined bona fide starburst sites of the highest SFE appear to be offsets from the peaks of the CO, radio continuum, FIR, and MIR emission. The future ultraluminous extreme starburst phase can possibly be reached once the CO concentrations in the overlap merge with the double-nucleus gas concentrations in the final coalescence.

7. In conclusion, our newly determined 5.7 times larger total molecular gas mass in the “Antennae” galaxies lowers the global SFE to be comparable with that of GMCs in the
We thank the NRAO 12 m telescope staff for generous support and additional allocations of the observing time.

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