STAR FORMATION ACROSS THE TAFFY BRIDGE: UGC 12914/15

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ABSTRACT

We present Berkeley-Illinois-Maryland Association (BIMA) two-field mosaic CO (1–0) images of the Taffy galaxies (UGC 12914/15), which show the distinct taffy-like radio continuum emission bridging the two spiral disks. Large amounts of molecular gas ($1.4 \times 10^{10} \, M_{\odot}$, using the standard Galactic CO-to-H$_2$ conversion applicable to Galactic disk giant molecular clouds) were clearly detected throughout the taffy bridge between the two galaxies, which, as in the more extreme case of H I, presumably results from a head-on collision between the two galaxies. The highest CO concentration between the two galaxies corresponds to the H$_\alpha$ source in the taffy bridge near the intruder galaxy UGC 12915. This H I region is also associated with the strongest source of radio continuum in the bridge and shows both morphological and kinematic connections to UGC 12915. The overall CO distribution of the entire system agrees well with that of the radio continuum emission, particularly in the taffy bridge. This argues for the star formation origin of a significant portion of the radio continuum emission. Compared with the H I morphology and kinematics, which are strongly distorted owing to the high-speed collision, CO better defines the orbital geometry and impact parameter of the interaction, as well as the disk properties (e.g., rotation, orientation) of the progenitor galaxies. Based on the 20 cm–to–CO ratio maps, we conclude that the starburst sites are primarily located in UGC 12915 and the H$_\alpha$ source in the bridge and show that the molecular gas in the taffy bridge is forming into stars with star formation efficiency comparable to that of the target galaxy UGC 12914 and similar to that in the Galactic disk.

Key words: galaxies: individual (UGC 12914, UGC 12915, VV 254) — galaxies: interactions — galaxies: ISM — galaxies: kinematics and dynamics — galaxies: starburst — radio emission lines

1. INTRODUCTION

Both observational evidence and theoretical perspectives show that galaxy interactions and mergers are one of the most important processes during the formation and evolution of galaxies. This is true both locally in the nearby universe and, in particular, cosmologically at high redshifts. Interaction/merger-induced starbursts, nuclear activity, feedback, and other associated phenomena, e.g., gas/dust transformation, infalls and outflows, play a critical role in shaping the interstellar medium (ISM) and intergalactic medium (IGM). Although almost all of the most luminous infrared galaxies (LIGs) and ultraluminous infrared galaxies (ULIGs) are known to be involved in mergers of gas-rich systems (see Sanders & Mirabel 1996 for a review), some gas-rich interacting galaxies that are not yet very infrared-luminous or active in star formation still lack thorough investigation. Why the interaction or merging in infrared-luminous or active in star formation still lack some gas-rich interacting galaxies that are not yet very gas-rich systems (see Sanders & Mirabel 1996 for a review), galaxies (ULIGs) are known to be involved in mergers of infrared galaxies (LIGs) and ultraluminous infrared galaxies (ULIGs) were clearly detected throughout the taffy bridge between the two galaxies, which, as in the more extreme case of H I, presumably results from a head-on collision between the two galaxies. The highest CO concentration between the two galaxies corresponds to the H$_\alpha$ source in the taffy bridge near the intruder galaxy UGC 12915. This H I region is also associated with the strongest source of radio continuum in the bridge and shows both morphological and kinematic connections to UGC 12915. The overall CO distribution of the entire system agrees well with that of the radio continuum emission, particularly in the taffy bridge. This argues for the star formation origin of a significant portion of the radio continuum emission. Compared with the H I morphology and kinematics, which are strongly distorted owing to the high-speed collision, CO better defines the orbital geometry and impact parameter of the interaction, as well as the disk properties (e.g., rotation, orientation) of the progenitor galaxies. Based on the 20 cm–to–CO ratio maps, we conclude that the starburst sites are primarily located in UGC 12915 and the H$_\alpha$ source in the bridge and show that the molecular gas in the taffy bridge is forming into stars with star formation efficiency comparable to that of the target galaxy UGC 12914 and similar to that in the Galactic disk.

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1 In this paper we use the following values: $d_L = 60$ Mpc, $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$.
after the collision. The highest H I column densities located in the taffy bridge are thus apparently a result of the stripped H I gas clouds owing to the direct cancellation of their motion after the counterrotating, interpenetrating, and head-on disk collision. It is conceivable that some GMCs were left behind in a similar way, although the chance of a head-on disk collision. It is conceivable that some GMCs motion after the counterrotating, interpenetrating, and H II disks are thus apparently a result of the stripped gas clouds owing to the direct cancellation of their motion after the counterrotating, interpenetrating, and head-on disk collision. It is conceivable that some GMCs were left behind in a similar way, although the chance of a head-on disk collision.

While little emission is found in the bridge/gap region in the optical and near-infrared wavelengths, the Hα image clearly reveals a distinctively separated H II region near the disk of the northeastern galaxy UGC 12915 (Bushouse & Solomon 1992). This H II region is also the strongest radio continuum site in the bridge. Jarrett et al. (1999) showed that there are several vigorous star-forming regions in and near UGC 12915, based on the Infrared Space Observatory (ISO) mid-IR images, and one corresponds to this extra-disk H II region. Condon et al. (1993) also noted that synchrotron emission from relativistic electrons trapped in the bridge nearly doubles the total radio luminosity expected from spirals based on the tight FIR/radio correlation (e.g., Helou, Soifer, & Rowan-Robinson 1985; Condon 1992).

Then the excess radio emission in the bridge may have little to do with the enhanced star formation. Is this indeed so?

There is also a ringlike pattern in the southwestern galaxy UGC 12914. The symmetric ring structure appears to be formed when the “intruder” galaxy UGC 12915 goes through the rotating disk of the “target” galaxy UGC 12914 (Appleton & Struck 1996; Gerber et al. 1990; Gerber, Lamb, & Balsara 1996; Struck 1997). The well-defined dynamical history of ring galaxies also makes the Taffy system an ideal candidate for studying the effect of galaxy interaction on the ISM and for understanding interaction-induced star formation.

All these observations and numerical modeling are somewhat hampered by the lack of knowledge of the detailed molecular gas distribution and kinematics, which are essential to understanding star formation and constructing the interaction history. Both the H I disk morphology and H I gas kinematics are too severely disturbed, and the spatial resolution is too low, to deduce the detailed galaxy disk kinematics of the precollision spiral pair. In comparison, molecular gas disks should suffer less damage in the early stage of galaxy interactions. CO imaging can thus better probe the star-forming gas distribution and kinematics of the progenitor galaxies, as well as current and future sites of star formation. Our high-resolution CO observations and multiwavelength comparisons might provide a Rosetta stone to shed light on more detailed numerical modeling incorporating the multiphase ISM (e.g., Struck 1997; Barnes 2002).

## 2. OBSERVATIONS

The 10-element Berkeley-Illinois-Maryland Association (BIMA) interferometer (Welch et al. 1996) is the most suitable millimeter instrument available at present to image the extended CO distribution and kinematics of the Taffy galaxies. This is because BIMA has a large field of view of ~2′ at 3 mm as well as short-baseline u-v coverage (the shortest baseline is ~7 m in the ultracompact D configuration). In addition, the flexible correlator configuration covers a rather broad velocity range. These characteristics are ideal for mapping extended CO emission of angular extent >40″.

Also, because the entire Taffy system extends over 2′–3′, we adopted two-field mosaicking with each field of view’s phase center pointing roughly near each galaxy’s nucleus. This gives a sufficient overlap between the two BIMA pointings over the taffy bridge, since the nuclear separation is 6″, much smaller than the BIMA primary beam (FWHM ~ 100″) for CO (1–0).

The observations were carried out during 1999 April–July. There were a total of 10 usable tracks accumulated for this project: six regular long (7–9 hr) tracks at both the ultracompact D and compact C configurations, plus four short (4–6 hr) tracks.

The on-source integration was equally split between the two fields after observing the nearby quasar 0010+109 several minutes for phase calibration. Uranus was also observed during each track in order to calibrate the antenna gains. Observations were carried out mostly under good/fair weather conditions. Details are summarized in Table 1.

Data reduction was performed mostly with MIRIAD. The maximum entropy method (MEM) was used only in deconvolution, although Sault, Staveley-Smith, & Brouw (1996) have implemented mosaicking algorithms that can use either CLEAN or MEM for simultaneous deconvolution.

All calibrated u-v data for the 10 BIMA tracks have been combined and inverted with the mosaic mode, and two sets

### TABLE 1

| No. | Obs. Date (1999) | Config. | Track Duration (hr) | T_{sys} (K) | No. of Antennas | Grade^a |
|-----|-----------------|---------|---------------------|------------|----------------|---------|
| 1   | Apr 27          | C       | 7.9                 | 290 ± 70   | 10             | B−      |
| 2   | Apr 29          | C       | 8.0                 | 310 ± 70   | 10             | B−      |
| 3   | May 6           | C       | 4.0                 | 330 ± 60   | 9              | C       |
| 4   | Jun 5           | C       | 9.0                 | 400 ± 110  | 10             | B−      |
| 5   | Jun 14          | C       | 6.7                 | 300 ± 70   | 10             | B      |
| 6   | Jul 12          | D       | 7.0                 | 340 ± 80   | 7              | C       |
| 7   | Jul 14          | D       | 5.6                 | 380 ± 90   | 7              | C       |
| 8   | Jul 15          | D       | 4.5                 | 360 ± 90   | 10             | B       |
| 9   | Jul 19          | D       | 5.5                 | 320 ± 70   | 9              | B       |
| 10  | Jul 27          | D       | 7.5                 | 290 ± 80   | 10             | B+      |

^a Overall grading based on system performance and weather conditions, etc., as given by duty observers: A: excellent, B: good, C: OK/usable, D: bad, and F: failure.
of channel maps were created with velocity resolutions of 20 and 40 km s$^{-1}$. The cleaned beam size is $9.9' \times 9.7'$, corresponding to natural weighting (robust = 1.2) in order to maximize the signal-to-noise ratio. We also produced a high-resolution data cube of uniform-weighting (robust = −1.0) with a synthesized beam of $5.0' \times 4.2'$, but throughout this paper we focus on the more sensitive low-resolution data cube because of its higher sensitivity and dynamic range. Further cleaning of the background noise was done in AIPS. Moment maps were then produced from the cleaned data cube. For comparison with the VLA H$\alpha$ results (Condon et al. 1993), we smoothed our CO data cube to the same 18$''$ resolution by Gaussian convolution.

3. RESULTS AND ANALYSIS

3.1. Molecular and Atomic Gas Distribution and Masses

Figure 1 presents the velocity-integrated CO intensity map (the moment zero map) in false color with the two overlapping BIMA fields. We now describe the main features in the CO distribution associated with each galaxy, namely, the molecular gas disks/rings and nuclear CO, the extra-disk CO concentration in the bridge coincident with the H$\alpha$ region, and the very extended, rather diffuse molecular gas in the taffy bridge. Both galaxies show nuclear CO concentrations, but UGC 12915 (the intruder) exhibits the strongest nuclear CO concentration. A significant quantity of CO in the bridge is associated with the H$\alpha$ region, which appears to be directly attached to the molecular disk of UGC 12915. This is much more clearly shown in the velocity channel maps of 20 km s$^{-1}$ width presented in Figure 2, which will be further detailed in the next section (§ 3.2). Moreover, the amount of molecular gas in the bridge between the galaxies appears to be comparable to that of UGC 12914 (the target).

Figure 3 presents the large-scale H$\alpha$ distribution of the Taffy system (Condon et al. 1993), with respect to optical structures. Obviously, the highest H$\alpha$ concentrations are in the bridge, and quite extended, rather than associated with the disks. Furthermore, nearly half of the total H$\alpha$ is located between the optical disks. The white contours in Figure 3 show the location of the H$\alpha$ peak as well as the half-maximum contour running through both optical disks. Unlike CO, which is mostly confined to the disks, H$\alpha$ is mostly located in the taffy bridge and the tidal tails, presumably the effects of ram pressure and tidal stripping. In fact, the H$\alpha$ disk morphology of the
Fig. 2.—Velocity channel maps of 20 km s$^{-1}$ width in contours overlaid on the DSS image. Top left of each panel labels the velocity (here zero corresponds to 4400 km s$^{-1}$). Contours start at 0.085 Jy beam$^{-1}$ (nearly 4 $\sigma$), and increase successively by a factor of $\sqrt{2}$. The last panel is the velocity-integrated (over the entire 800 km s$^{-1}$ range) CO intensity map (the moment zero map as in Fig. 1). Here contours start at 32.5 Jy km s$^{-1}$ beam$^{-1}$ and increase by a factor of $\sqrt{2}$. 
individual galaxies has mostly disappeared although it is kinematically recognizable, and the two \( \text{H} \) \( \text{I} \) disks seem to have already merged into one system.

UGC 12914 has prominent stellar ring structures, which are also clearly visible in the Digitized Sky Survey (DSS) image (Figs. 2 and 3). Unlike the luminous infrared ring galaxy NGC 1144, where huge CO concentrations are distributed along the rings (Gao et al. 1997), little molecular gas is detected in the ring of UGC 12914. However, the \( \text{H} \) \( \text{I} \) brightness might peak on part of the ring, and weaker \( \text{H} \) \( \text{I} \) concentrations appear to follow the ring structures (Fig. 3), although the limited spatial resolution does not allow any detailed comparisons. Secondary CO concentrations are also obvious in both galaxies, most likely indicating the locations of the rotating CO rings/disks.

We estimate the CO fluxes over different regions, as well as the total CO flux of the entire system, using both the velocity-integrated CO intensity (moment zero) map (Fig. 1) and the velocity channel maps (Fig. 2). From optical images, different regions such as disks, rings, and \( \text{H} \) \( \text{II} \) regions can be rather easily defined, although no distinct taffy feature is visible. The exact division of different CO regions is not well defined, however. For instance, CO emission from the extra-disk \( \text{H} \) \( \text{II} \) region is intimately connected to the CO disk of UGC 12915, which is mildly distorted. And it is difficult to assign the exact borderlines separating different regions even in the velocity channel maps (Fig. 2). In particular, the separation of the \( \text{H} \) \( \text{II} \) region from the diffuse taffy bridge CO is arbitrary. The adopted values based on our measurements over various regions are summarized in Table 2.

It is also difficult to distinguish the extended CO bridge from the CO that is possibly associated with part of the ring structures and the weak CO near the strongest \( \text{H} \) \( \text{II} \) emission peak (Fig. 3), even using the CO velocity channel maps. This is due partly to the limits imposed by the spatial resolution, particularly in the \( \text{H} \) \( \text{I} \) observations, the sensitivity of our observations, and partly to the rather diffuse nature of the neutral gas (both molecular and atomic) in the bridge. Also, the CO fluxes can increase by up to \( \sim 20\% \) if weaker extended regions of lower signal-to-noise ratio (\( \lesssim 3 \sigma \)) are included.

Using the standard CO-to-H\(_2\) conversion, \( X \equiv N(\text{H}_2)/I_{\text{CO}} = 3.0 \times 10^{20} \text{cm}^{-2} \text{(K km s}^{-1})^{-1} \), applicable to Milky Way disk GMCs, we can estimate the molecular gas mass in different regions across the system. We obtain the molecular gas mass directly from the estimated CO fluxes \( (f_{\text{CO}} = \int S_{\text{CO}} dv) \) in Table 2, using \( \frac{M_{\text{H}_2}}{M_\odot} = 1.18 \times 10^4 D_L^2 f_{\text{CO}} \), where \( D_L \) is the luminosity distance in megaparsecs, which is equivalent to the standard CO-to-H\(_2\) conversion. Note the conversion from janskys per beam to Kelvins for the synthesized beam of \( 9.9 \times 9.7 \) is \( 0.99 \text{ K} \) (Jy beam\(^{-1}\))\(^{-1}\). We thus obtain the total molecular gas masses of UGC 12914, UGC 12915, the \( \text{H} \) \( \text{II} \) region, and the Taffy bridge to be \( (1.3, 1.5, 0.4, \text{and} 1.4) \times 10^{10} M_\odot \), respectively.

Several papers have reported single-dish CO observations of the Taffy system. Smith & Struck (2001) observed nine pointings using the former NRAO 12 m telescope and yielded five detections. They reported molecular gas masses of \( 1.9 \times 10^{10} \text{ and } 1.7 \times 10^{10} M_\odot \) for UGC 12915 and 12914, respectively. An upper limit of \( \lesssim 1.9 \times 10^{10} M_\odot \) was also

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**TABLE 2**

CO Measurements of the Taffy Galaxies

| Source          | \( f_{\text{CO}} \) (Jy km s\(^{-1}\)) | \( V_{\text{CO}} \) (km s\(^{-1}\)) | \( M(\text{H}_2) \) \( (10^6 M_\odot) \) | \( M(\text{H} \text{I}) \) \( (10^5 M_\odot) \) | \( M_{\text{dust}} \) \( (10^3 M_\odot) \) | \( L_{\text{IR}} \) \( (10^9 L_\odot) \) | SFE\(^{a} \) \( (L_\odot/M_\odot) \) |
|-----------------|-------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| U12915          | 355               | 100             | 1.5             | 0.4             | 5.              | 3.3             | 11              |
| U12914          | 315               | -60             | 1.3             | 0.5             | 6.              | 1.4             | 4               |
| H \( \text{II} \) region | 90               | 90              | 0.4             | 0.06            |                |                 |                 |
| Bridge\(^{e} \) | 325               | 90              | 1.4             | 0.6             | 3.4             | 4               |                 |
| H \( \text{I} \) peak\(^{e} \) | \( \lesssim 30 \) |                 | 0.1             | 0.08            |                 |                 |                 |

\(^{a}\) Zero velocity corresponds to 4400 km s\(^{-1}\).

\(^{b}\) Estimated by roughly scaling according to the 20 cm radio continuum emission.

\(^{c}\) Highest estimated from the SFE \( = L_{\text{IR}}/M(\text{H}_2) \) map in Fig. 7.

\(^{d}\) Entire bridge including the H \( \text{II} \) region and H \( \text{I} \) peak. But the highest SFE is referring to regions excluding the H \( \text{II} \) region and H \( \text{I} \) peak.

\(^{e}\) The H \( \text{I} \) peak region in an 18\'' beam.
given for the taffy bridge. Judging from the CO image, both of the 12 m beams pointing at UGC 12915 and at the taffy bridge completely cover the dominant extra-disk CO feature. Thus, the molecular gas mass from the taffy bridge excluding the CO concentration at the H\textsc{ii} region should be much less than this upper limit. Overall, a total molecular gas mass of $\sim 4.5 \times 10^{10} M_\odot$ for the whole system seems to be in excellent agreement with our BIMA results.

Zhu et al. (1999) and Zhu (2001) also reported the total fluxes of the Taffy system based on their observations with the NRAO 12 m and IRAM 30 m telescopes. Both measurements are in excellent agreement with our BIMA results. The IRAM observations (Braine et al. 2003) map the entire system at $CO$ $J = 1 - 0$ and $2 - 1$ transitions with $11''$ spacing. The comparison of the BIMA interferometer data and the IRAM single-dish data shows that the BIMA map has recovered virtually all the CO flux within the calibration uncertainty of 20%. The quantitative study of the excitation of the molecular gas in this system combining the CO data and H\textsc{i} of $6 \times 10^{10} M_\odot$, assuming a single dust temperature, but including cold dust with $T_{\text{cold}} = 20$ K can increase the dust mass by a factor of 2 (L. Dunne 2003, private communication). Also, there may be significant diffuse emission between the galaxies that is not yet detected. Thus, the actual dust mass can be much higher than the value reported above.

The H\textsc{i} gas mass (Table 2) can be estimated using $M_{\text{H\textsc{i}}}(M_\odot) = 2.36 \times 10^4 D_s^2 \int S_{\text{H\textsc{i}}} \, dv$, where $\int S_{\text{H\textsc{i}}} \, dv$ is the H\textsc{i} integrated flux in $Jy$ km s$^{-1}$ s$^{-1}$. We use the estimated H\textsc{i} fluxes from the total H\textsc{i} line emission map shown in Figure 3.

For a total gas mass (both H\textsc{i} and H\textsc{2}) of $6 \times 10^{10} M_\odot$, we expect the total dust mass to be on the order of $3 \times 10^{10} M_\odot$ assuming a Galactic dust-to-gas mass ratio of 1/200.

This value, based purely on the empirical gas-to-dust ratio, thus constrains the CO-to-H\textsc{2} conversion factor $X$ (see § 4.3.1). Future more sensitive submillimeter measurements, including 450 $\mu$m with the Submillimeter Common-User Bolometric Array (SCUBA) on the James Clerk Maxwell Telescope as well as SIRTF FIR observations, will firmly settle these issues.

### 3.2. The Gas Kinematics

In the velocity channel maps, rather detailed radial velocity information and the kinematic relationship of the various structures can be identified (Fig. 2).

The molecular gas in the southwestern galaxy (UGC 12914, the target) first appears at $\sim 360$ km s$^{-1}$ (4040 km s$^{-1}$) in the inner part of the hooklike structure near northwestern edge of the stellar disk. With increasing velocity, CO emission shifts systematically toward the southeast along the stellar disk and eventually disappears around 280 km s$^{-1}$ (4680 km s$^{-1}$). The much stronger CO in UGC 12915 (the intruder) first becomes prominent at $\sim 200$ km s$^{-1}$ (4200 km s$^{-1}$), but may show a much fainter signature starting as low as $\sim 360$ km s$^{-1}$ (4040 km s$^{-1}$). The rather strong molecular gas concentrations in the intruder disk move with increasing velocity toward the northwest, following the expected rotation pattern. The molecular gas in UGC 12915 shows a direct kinematic connection with the strongest CO concentration in the bridge, and disappears entirely beyond $420$ km s$^{-1}$ (4820 km s$^{-1}$). The high-velocity CO in the intruder is associated with the dusty patches in the northwest, which are evident in the DSS image. This indicates the progenitor disk of the intruder is slightly more tilted, relative to the target galaxy’s disk, than that which appears in the DSS image. Both the northwestern stellar extension and the southeastern fainter edge are possibly related to the tidal features produced during collision. This is also evident by examining the Two Micron All Sky Survey (2MASS) images, which clearly show that the underlying stellar disk of the intruder galaxy is confined to the dusty patches in the DSS image. The sense of the rotation of the two molecular gas disks is exactly opposite. Thus, both disks have molecular gas in counterrotation at speeds exceeding 300 km s$^{-1}$, even after the direct, interpenetrating, head-on collision.

The molecular gas in the taffy bridge has a much smaller velocity range than the velocity spread of the two counter-rotating molecular disks. Nevertheless, this material has a velocity spread of over 200 km s$^{-1}$. The emission emerges at $\sim 60$ km s$^{-1}$ (4340 km s$^{-1}$), becomes progressively more prominent around 80 km s$^{-1}$ (4480 km s$^{-1}$), and disappears at $\sim 200$ km s$^{-1}$ (4600 km s$^{-1}$). The velocity spread of the strongest CO feature in the bridge, the H\textsc{ii} region adjacent to the intruder galaxy, is identical to that of the CO emission over the entire bridge region. These features are perhaps better represented in the first moment (velocity field) and second moment (velocity line width) maps shown in Figure 4. These moment maps (Figs. 1 and 4) are derived from the detailed velocity channel maps (Fig. 2).

In summary, the CO kinematics and the overall CO morphology reveal two rapidly counter-rotating CO disks ($\geq 300$ km s$^{-1}$), with a fairly large amount of extended CO emission in the bridge. The CO emission in the bridge, including the concentration at the H\textsc{ii} region, occupies a much smaller velocity spread than the rest of the system (Fig. 4b), yet its mean velocity is about the same as the systemic velocity of the whole.

Using the convolved CO data cube (to match the 18$''$ resolution of the H\textsc{i}) and the VLA H\textsc{i} data cube, kindly provided by J. Condon, we constructed the position-velocity (P-V) diagrams presented in Figures 5a and 5c. For both galaxies, the P-V maps show that the H\textsc{i} and CO are distributed roughly in the same velocity range, but the H\textsc{i} spans a much larger spatial extent. In particular, for both CO and H\textsc{i} along the major axes, the P-V plots clearly show the rotation pattern of the gas disks.

To reveal more clearly the differences between the H\textsc{i} and CO gas properties in the bridge, we also show an additional P-V diagram across the bridge (Fig. 5b). The P-axis joins the nuclei of the two galaxies and passes through the CO concentration in the H\textsc{ii} region. Clearly, there are two velocity components in H\textsc{i} at $\sim 4500$ and $\sim 4250$ km s$^{-1}$, whereas almost the entire CO emission in the bridge has only the $\sim 4500$ km s$^{-1}$ component. In addition, a clear kinematic connection between the intruder UGC 12915 and the CO in the bridge is evident from this P-V plot since the cut is roughly along the minor axis, going through the H\textsc{ii} region and the bridge.

Evidently, CO in both galaxy disks retains the signature of the solid-body rotation pattern, whereas the H\textsc{i} disks are
certainly distorted and/or lopsided (Figs. 5a and 5c). In both H\textsc{i} gas disks, the distortion/lopsidedness is associated with the higher velocity parts. In fact, the extended H\textsc{i} emission appears to be reminiscent of the long H\textsc{i} tidal tails observed in most galaxy mergers. In extreme cases like the Antennae galaxies, more than half of H\textsc{i} appears to end up in the H\textsc{i} tidal tails (Hibbard et al. 2001a).

The foregoing comparisons indicate that both CO disks have mostly survived the head-on collision and retained \( \gtrsim 300 \) km s\(^{-1}\) rotation velocity (Figs. 5a and 5c), whereas the H\textsc{i} disks have been disrupted, exhibiting smaller rotation velocity than that of CO and possessing a very asymmetric distribution, both spatially and kinematically, owing to the strong disk collision.

In Figure 6, the grid spectra of both CO and H\textsc{i} in the bridge gap also show a distinct difference: one peak for CO but a double-peak for H\textsc{i}. Obviously, CO is associated with the higher velocity H\textsc{i} component in the bridge.

From the H\textsc{i} channel map shown in Figure 5 of Condon et al. (1993) and the overall H\textsc{i} morphology (Fig. 3), it is also evident that both of the H\textsc{i} disk extensions and the H\textsc{i} tidal tails (toward the southeast of the target and northwest of the intruder) are in the higher velocity ranges. But the severe damage in the H\textsc{i} disks is more associated with the lower velocity H\textsc{i}, which is now mostly in the taffy bridge. This is also clearly shown in the P-V plots (Fig. 5), particularly in the target galaxy UGC 12914, where most of the lower velocity H\textsc{i} has been stripped away and left behind in the bridge.

From the spatial distribution of both the CO and H\textsc{i} in the bridge, it may be seen that there is almost no CO detected coincident with the H\textsc{i} peak position (Figs. 1–3). This is clearly revealed from the CO (Fig. 2) and H\textsc{i} (Fig. 5 in Condon et al. 1993) channel maps over roughly the same velocity range in the bridge. Most of the CO in the bridge is in the H\textsc{ii} region and to the south of the H\textsc{i} peak, which might be related to the ring structures of the target galaxy. This is partly reflected in the P-V plot cutting through the bridge (Fig. 5b), as well as the spectra of H\textsc{i} and CO near H\textsc{i} peak (Fig. 6). Except for the H\textsc{i} extensions/tails associated with the tidal features in the galaxy disks, most of the H\textsc{i} is rather extensively distributed across the bridge in two distinct velocity ranges and possibly originates from both galaxies.

### 3.3. Star Formation Efficiency Map

The ratio of \( L_{\text{IR}}/M(\text{H}_2) \) (\( \sim 2 L_\odot/M_\odot \) for the Taffy system) is often referred to as the global SFE since the total FIR emission, the tracer of the global star formation rate, has been normalized by the total molecular gas mass available to make stars. Similarly, we can quantify the local star formation properties by measuring the local SFE. We have localized measurements of the molecular gas mass from CO maps. Here we characterize the star formation rate simply by using the radio continuum emission as a surrogate for the FIR emission (see § 4.2; also Murgia et al. 2002). We thus obtain the radio-to-CO ratio map to reveal the variation in the local SFE. A successful application of this technique to the Antennae galaxies can be found in Gao et al. (2001b). The VLA 20 cm continuum (Condon et al. 1993) and our CO maps have roughly comparable spatial resolution. Thus, a direct division can be obtained once the 20 cm continuum map has been regridded to match the pixel scale of the CO map.

Remarkably, the local 20 cm/CO ratio (Fig. 7) changes in most cases only by factors of a few and stays roughly constant over the bulk of the molecular gas distribution. The lowest contour plotted is the geometric mean of the minimum and maximum of the 20 cm/CO ratio.

Successive contours increase by a factor of \( \sqrt{2} \). The peak contour is only a factor of 5 larger than the average. The highest SFE sites, with an SFE \( \gtrsim 11 L_\odot/M_\odot \), are in the nuclear region and in the inner edges of the molecular gas ring/disk of UGC 12915. The adjacent extra-disk starburst site (the H\textsc{ii} region) in the bridge has an SFE \( \gtrsim 7 L_\odot/M_\odot \), nearly twice that of the Galactic GMCs. The inferred SFE across most of the taffy bridge is comparable to the highest found in the nuclear region of the target galaxy UGC 12914, which is about the same as that of the Galactic GMCs. The...
region around the highest \(\text{H} \text{i}\) peak, where little CO emission is found, has slightly higher SFE than even the nuclear region of UGC 12914.

Therefore, the sites of highest SFE are exclusively associated with the possible starburst sites in the intruder. Other plausible active star-forming sites of modest SFE are perhaps in the taffy bridge, one at the \(\text{H} \text{i}\) region, and the other near the highest \(\text{H} \text{i}\) column density. The other regions in the taffy bridge as well as the target galaxy have normal SFEs, comparable to that of Galactic GMCs, and are thus just normal star-forming sites.

3.4. The Multiwavelength Comparison

Figure 8 presents near-IR H-band, ISO mid-IR 15 \(\mu\)m (Jarrett et al. 1999), VLA 20 cm continuum, and \(\text{H} \text{i}\) line emission (Condon et al. 1993), overlaid with CO contours. Although it is quite faint, the \(\text{H} \text{i}\) region also shows up in the near-IR image (Fig. 8a). Even 2MASS images appear to indicate some faint emission at the \(\text{H} \text{i}\) region. This \(\text{H} \text{i}\) region is also evidently present in the 15 \(\mu\)m image (Fig. 8b), although it is not certain whether other mid-IR features in the taffy bridge are real or not.

The best match in Figure 8 is between the radio continuum and the CO emission, including the taffy bridge. Most of the main features, either in the disks or in the taffy bridge, appear in both 20 cm and CO images (Fig. 8c). However, it is noticeable that the northern portion of the taffy bridge, evident in radio continuum, is rather deficient in CO emission. The deficiency in CO in some locations is likely real, in particular, some small gaps appearing in the SFE contour map (Fig. 7) due to the lack of CO emission there. The comparison between CO and \(\text{H} \text{i}\) (Fig. 8d) indicates that most of the extended \(\text{H} \text{i}\) concentrations are systematically shifted toward the northwest relative to most CO emission in the bridge.

With all observations combined, in particular, the CO and \(\text{H} \text{i}\) kinematics, we may better constrain the various parameters of the two galaxies. Given the strong distortion of the \(\text{H} \text{i}\) morphology/kinematics, parameters like the maximum corrected rotation velocity \(V_{\text{max}}\) at radius \(R_{\text{max}}\) are better deduced from CO data. This is because the molecular gas disks have suffered less disruption than the \(\text{H} \text{i}\) disks. Furthermore, the inclination of UGC 12915, determined from the near-IR morphology, is slightly less than that apparent in the optical image (Fig. 6a). The tidal feature elongated toward the northwest leads to a slightly higher estimate of the inclination. Compared with published values (Giovanelli et al. 1986) we use an inclination of \(\sim 70^\circ\) rather than \(73^\circ\) for UGC 12915, and \(61^\circ\) for UGC 12914, identical to the previously published value.

The observed CO velocity line widths are \(W = 600\) and \(580\) km s\(^{-1}\) for UGC 12915 and UGC 12914, respectively, and thus \(V_{\text{max}} = 315\) and \(327\) km s\(^{-1}\) after the inclination and redshift broadening corrections. In comparison, the \(\text{H} \text{i}\) line widths of \(510\) and \(550\) km s\(^{-1}\) and \(V_{\text{max}} = 260\) and \(310\) km s\(^{-1}\) were given for UGC 12915 and UGC 12914, respectively, by Condon et al. (1993). Note that the value of \(R_{\text{max}}\) estimated from \(\text{H} \text{i}\) data might be too large owing to the contamination by the \(\text{H} \text{i}\) tidal features. Therefore, we use CO data that give \(R_{\text{max}} = 0.41\) and \(0.25\) to estimate the dynamical masses of UGC 12914 and UGC 12915, which are \(4.5 \times 10^{11}\) and \(2.6 \times 10^{11}\) \(M_\odot\), respectively.
4. DISCUSSION

4.1. The Gas Pileup and Dynamics in the Taffy Bridge

When two counterrotating gas disks collide at high speed, the diffuse gas clouds (mainly H\(_i\)) collide at highly supersonic speeds. Thus, we can expect an extensive “gas splash,” and possibly other observable effects of shock heating and radiative cooling as probed by numerical simulations (Struck 1997; Barnes 2002). The Taffy system is unique, with a nearly face-on collision, and the relative collision speed of the H\(_i\) clouds is nearly 900 km s\(^{-1}\), since the estimated transverse collision speed of the two galaxies is about 600 km s\(^{-1}\) (Condon et al. 1993). The velocities of the H\(_i\) clouds could be essentially canceled after a direct, counterrotating, and dissipative head-on collision. Apparently the molecular gas disks have mostly survived the collision. However, the H\(_\text{II}\) region, however, may have been recently formed out of the extradisk molecular gas concentration that has been pulled out of the molecular gas disks and condensed after the collision.

A simple estimate can be made for the amount of H\(_i\) left in the taffy bridge. For a perfect face-on disk collision with the same counterrotating speed, all H\(_i\) clouds in two galaxies that have collided inelastically will be left behind after the collision. Essentially almost all diffuse gas could be pulled out of the disks when the collision velocity is much smaller than the rotation speed. When the collision speed is much larger than the rotation speed, however, the amount of gas that collides will be less, depending on the exact area of the disk-to-disk overlap and the amount of area of the disks that has been swept owing to the counterrotation during their close impact. The Taffy system falls between the two extreme cases since the collision speed is comparable to the counterrotating speed.

Judging from the multiwavelength images, particularly the radio continuum and H\(_i\) maps compared with the CO (Fig. 8), the intruder may have collided with the inner nuclear region and the entire northwestern portion of the target disk with an angle of nearly 30° between the major axes. According to Toomre & Toomre (1972), the impact parameter should be smaller than the disk radii in order to produce the ring structures, rather than prominent tidal tails. However, there are weak tidal features present. Thus, the impact parameter cannot be much smaller than the disk radii either, since numerical simulations show that encounters with impact parameters larger than the galactic radii can be most effective in producing long tails and stronger gas inflow toward the nuclei. Given these considerations, most of the southeastern portion of the target disk might be much less damaged. A small portion of the intruder’s H\(_i\) disk in the northwest may have suffered less impact as well, owing to this particular impact configuration. Judging from the H\(_i\) distribution in Figure 3, we can assume that more than one-third of the H\(_i\) clouds in the target galaxy reside in the southeastern disk and about one-third of the H\(_i\) gas in the intruder galaxy is located in its northwestern disk. Then most of the H\(_i\) in the intruder and the H\(_i\) in the northwestern portion of the target galaxy, totalling about half of the total H\(_i\) gas of the system, could have experienced a collision, owing to the sweeping of the counterrotating disks, with the remnants mostly left behind.

![Image of DSS contours compared with the near-IR K\(_s\) image indicating the underlying stellar disk is slightly less tilted. The dashed box outlines the area in the bridge within which the 7 × 5 grid spectra (right) at 9° spacing for both CO (thin line) and H\(_i\) (thick line) were extracted. The labels (lower left spectra) are only for CO flux in janskys per beam, and the velocity range is 3900–4860 km s\(^{-1}\).](image-url)
in the taffy bridge. A direct comparison of the H i morphology with the CO image and the stellar disks (Fig. 8) appears to indicate that indeed nearly \( \sim 50\% \) of the H i is located in the taffy bridge between the two disk galaxies.

Our BIMA CO maps obviously reveal abundant H\(_2\) gas in the bridge. In particular, there is a high concentration of molecular gas near the intruder, coincident with the H\(\alpha\) source, clearly indicating an active extra-disk star-forming region. The spatial distribution and kinematics of the CO along the bridge suggest that most CO is, in fact, the gas splash following the interpenetration of the two inner molecular disks. Interestingly, except for the ring structures and the molecular gas concentration in the H\(\Pi\) region, little on-going star formation is detected in the bridge. The dust extinction, resolution, and sensitivity could all be contributing factors for detecting few stars. Although the peak H i column density at the taffy bridge is only \( 3 \times 10^{21} \) cm\(^{-2}\), as measured by the VLA 18\(''\) beam, the CO emission observed by the BIMA 10\(''\) beam in the bridge actually dominates the column densities (using the standard CO-to-H\(_2\) conversion factor). The lowest column densities in the bridge detected in CO are in fact several times larger than the peak H i column density. The estimated extinction near the H i peak region, where the CO is weakest, could still be quite high, with \( A_V \gtrsim 10 \) mag.

In addition to the obvious starburst site of the H\(\Pi\) region in the bridge, the huge amount of H i piled up between the two galaxies could be the potential sites for the development of overlapping starbursts, which are quite common in interacting galaxies (Xu et al. 2000). Such large H i gas concentrations are also found in galaxies of different interaction geometry, e.g., NGC 6670 which involves an edge-on collision (Wang et al. 2001). It is conceivable that once the H i concentrations condense further, and perhaps form self-gravitating systems, they could capture some GMCs passing by and could also possibly convert some H i into molecular form. An extreme example with prominent overlapping starbursts is the Antennae galaxies, where more than 50\% of the total CO emission is found in the overlap region (Gao et al. 2001b). In the Taffy system, the huge H i concentration between galaxies might then provide a mechanism for an eventual molecular concentration in the bridge region.

High-speed (900 km s\(^{-1}\)) gas cloud collisions should produce shock waves heating the gas to more than \( 10^7 \) K. It would be interesting to map the hot ISM of the taffy bridge and further compare the gaseous structures of different phases of the ISM. The Taffy system appears to be an intermediate example, bridging the slow-speed (\( \sim 300 \) km s\(^{-1}\) or less), gas-rich merging galaxies and the very high speed (\( \sim 1000 \) km s\(^{-1}\)) encounters in compact groups of galaxies. In most merging systems, H i appears to roughly follow the distribution of the stars during the encounter, whereas huge H i reservoirs, located far away and completely outside of the galaxy disks, can often be found in compact groups of galaxies (e.g., HCG 92; Williams, Yun & Verdes-Montenegro 2002). Also in HCG 92, CO is found in the surrounding IGM.

Fig. 7.—The 20 cm–to–CO ratio, contours overlaid on the CO image. The first contour corresponds roughly to SFE \( \sim 2 L_\odot/M_\odot \), the rest increase successively by \( \sqrt{2} \). The 20 cm–to–CO ratio could be interpreted as SFE if the 20 cm continuum is indicative of the star formation rate.
H\textsubscript{i} concentrations (Gao & Xu 2000; Lisenfeld et al. 2002). Prominent large-scale H\alpha and soft X-ray emission, presumably related to the H\textsubscript{i} splashes and shock wave heating, are also evident in HCG 92 (Trinchieri et al. 2003).

4.2. Star Formation across the Taffy Bridge between the Galaxies

It is tempting to interpret the 20 cm–to–CO ratio as an SFE map (Fig. 7) because the radio continuum emission can be used as a tracer of the recent star formation in galaxies (e.g., Condon et al. 1996; Condon 1992). In particular, there is an excellent correlation between the FIR and radio continuum emission (Helou et al. 1985; Condon 1992; Xu et al. 1994; Yun, Reddy, & Condon 2001), and the tight FIR/radio correspondences appear also to be valid at least on kiloparsec scales in galaxies (e.g., Marsh & Helou 1995; Lu et al. 1996). Murgia et al. (2002) analyzed the 20 cm/CO ratio in a large sample of star-forming galaxies and showed that it remains constant within a factor of 3 (with a resolution of about 50\arcsec), both inside the galaxies and from galaxy to galaxy. Nevertheless, it is still debatable whether the radio continuum emission in the taffy bridge is a good indicator of star formation. Condon et al. (1993) noted that the synchrotron emission from relativistic electrons trapped in the bridge nearly doubles the total radio luminosity expected from normal spirals. Thus, it is possible that the star formation rate estimated from the radio continuum could be overestimated at most by a factor of 2 since synchrotron emission from relativistic electrons accelerated in gas collision shocks may contribute a significant fraction of the

Fig. 8a

Fig. 8b

Fig. 8c

Fig. 8d

Fig. 8.—CO contours compared with the multiwavelength images of (a) the near-IR H\textsubscript{\alpha} band, (b) ISO mid-IR 15 \textmu m, (c) VLA 20 cm radio continuum, and (d) 21 cm H\textsubscript{i} line. The CO contours of 22.5, 25, 27.5, 30, 35, 40, 50, 60, 70, 80, 90, and 99 percent of the peak emission are plotted in all panels.
radio continuum. The close correlation between CO and radio continuum, particularly in the extended taffy bridge (Fig. 8c), however, may imply that most of the radio continuum emission could still be related to the very recent ongoing star formation (e.g., Murgia et al. 2002). The radio continuum might be directly associated with the various by-products of the star formation process, such as supernovae remnants, and is therefore still a useful indicator of the (FIR) star formation.

The gas (H\textsuperscript{i} + H\textsubscript{2}) surface density in the bridge is significantly higher than the threshold for star formation as suggested by the spatially resolved study of normal spirals (Martin & Kennicutt 2001). The H\textsuperscript{i} gas alone in the bridge, as mapped by the 18" VLA beam, is about 20 M\textsubscript{\odot} pc\textsuperscript{-2} (the second white contour outlining the H\textsuperscript{i} gas between the two galaxies in Fig. 3). The H\textsubscript{2} gas surface density is much higher, and the minimum detected by the 9\textdegree9 × 9\textdegree7 beam, using a standard conversion factor X, is as large as 150 M\textsubscript{\odot} pc\textsuperscript{-2}. Therefore, essentially all regions with CO detection have molecular gas surface density about 1 order of magnitude above the mean star formation threshold in normal spiral galaxies. It should be noted that the H\textsuperscript{i} peak region could be the overlap of two H\textsuperscript{i} arms (one arm from UGC 12915 and the other from UGC 12914), given the two distinctively different velocities in the bridge (Fig. 6). The actual H\textsuperscript{i} column density at the H\textsuperscript{i} peak regions could thus be a factor of 2 lower. However, the combination of the H\textsuperscript{i} and H\textsubscript{2} (even with a conversion factor X 10 times smaller) still yields a gas surface density higher than the threshold for star formation in normal galactic disks.

4.3. Is the Taffy System in a Starburst Phase?

Star formation occurs within GMCs, especially the dense cores where stars are forming with SFEs orders of magnitude higher than the average. Interestingly, local starburst galaxies have SFEs higher (by factors of 2–5) than normal spiral galaxies, whereas almost all LIGs/ULIGs have SFE ≥ 20 L\textsubscript{\odot}/M\textsubscript{\odot}, or even orders of magnitude higher than normal spirals (Sanders & Mirabel 1996). However, there are some early stage premerging LIGs with SFE ~ 10 L\textsubscript{\odot}/M\textsubscript{\odot} and lower, such as Arp 302 (Gao 1996; Lo et al. 1997). Across most of the active star-forming regions in the Taffy system, however, starbursts are not particularly strong. Apart from the nuclear region of the intruder and its edge-brightened inner CO disk/ring, the H\textsuperscript{i} region in the bridge barely qualifies as a true starburst site simply based on its SFE. Since the average SFE of the Galactic disk GMCs is a factor of 2 higher than the global SFE of the Taffy system, the entire system seems not to be a starburst at all. Unless we have seriously overestimated the molecular gas mass by using the standard CO-to-H\textsubscript{2} conversion, almost all molecular gas in the taffy bridge and in the target galaxy has a low SFE and is not in the starburst phase.

The same argument may apply to both the intruder and the target galaxies as well since a much smaller molecular gas mass will result in an extremely high SFE, which also appears to be inappropriate, in particular, because the Taffy system is itself not yet a genuine LIG system. The tight correlation between radio continuum and CO may actually indicate that the bulk of radio continuum emission in the taffy bridge is probably related to the globally normal star formation. And it is the large-scale star formation in addition to some localized modest starbursts that power most of the energy output in the Taffy system.

4.3.1. Effect of the CO-to-\textsubscript{H}_2 Conversion Factor

Any reduction of the conversion factor X in the Taffy system will result in an enhanced SFE by the same factor. If we sufficiently overestimate the molecular gas mass in the intruder, then the intruder could clearly be a strong starburst. Similarly, if a smaller conversion factor X is used in the bridge, the molecular gas there could then be forming into stars with elevated SFE as well, even after lowering the star formation rate by a factor of 2 to bring it in line with the FIR/radio correlation. It is important to note in this context that the conversion factor X in ULIGs is significantly lower than in Galactic GMC’s. In a ULIG, however, extremely high nuclear gas concentrations around the merged double-nucleus have resulted in such extraordinarily high molecular gas density that even the intercloud medium is molecular. Thus, most of CO detected in ULIGs is not from self-gravitating GMCs. Nevertheless, even under such extreme conditions, the reduction in the conversion factor X is only a factor of ~5 (Downes & Solomon 1998). Judging from the comparatively lower CO concentrations in the target galaxy UGC 12914, it is unlikely that such an overestimation of molecular gas occurs in this galaxy. However, this could be the case in the intruder galaxy in which CO is rather highly concentrated.

However, given the mostly low concentrations of CO and the lack of independent evidence for high star formation activity, it is unlikely that we have overestimated the molecular gas mass by a large factor, and we conclude that star formation is probably rather inactive over the bulk of the molecular gas in the Taffy system.

4.4. The Taffy Galaxies As a Future Starburst System

Like the Taffy system, many interacting systems show little or no enhanced new star formation, while statistically as a whole, they only show a factor of 2 enhancement compared with normal spirals (Xu & Sulentic 1991). Half of an objectively selected sample of eight interacting systems imaged by ISOCAM show no particularly obvious starbursts (Xu et al. 2000). It is not surprising that high-speed splashes and shock wave heating may inhibit star formation since they disrupt disk clouds and lead to an overall rarefaction of disk gas, and thus only some regions that have built up enough gas concentration can actually be actively forming into stars and are thus in a starburst phase.

Yet it seems clear that interaction as well as the associated gas-infall and high-pressure compression of GMCs (e.g., Jog & Solomon 1992) are important for triggering enhanced star formation, though it may only be preferred in mergers with a relatively slow-speed encounter. In any case, it appears that such high-pressure compression might only be the initiator of a multi-step process. The Taffy system could have just experienced a strong starburst phase a few tens of millions years ago (Stab, separation/V\textsubscript{transverse} ~ 3 × 10\textsuperscript{7} yr) at the closest splash of the two disks. We could perhaps also expect a future starburst once the two galaxy disks collide/splash again and eventually merge into one system. The molecular gas in the bridge is on average forming stars at a rate of ~6 M\textsubscript{\odot} yr\textsuperscript{-1} (L\textsubscript{IR} = 3.4 × 10\textsuperscript{10} L\textsubscript{\odot}). It has potential for future starburst with a ten-fold increase of L\textsubscript{IR} in the
next few tens of millions of years as the gas depletion time is more than 2 Gyr.

4.5. Uniqueness of the Taffy Phenomenon and High-Redshift Implications

Recently a second taffy pair VV 769 = UGC 00813/16 was discovered (Condon, Helou, & Jarrett 2002), and the radio continuum and H i line images show many similarities to that of UGC 12914/15. This is remarkable since such systems indeed seem to be rare in the local universe (Condon et al. 2002). Nevertheless, systems with a radio continuum emission bridge between the two galaxies do exist, e.g., Arp 270 (NGC 3395/96) observed by Huang et al. (1994), although they are not as dramatic as the prominent taffy bridge in UGC 12915/14. On the other hand, a substantial population of IR luminous galaxies with dust much cooler than the local LIGs may exist at moderate to high redshifts (Chapman et al. 2002). There is also some indication that there may be a high-redshift population of submillimeter sources with excess radio emission compared with the IR/radio correlation for local galaxies. The Taffy system does have excess radio continuum emission in the bridge and perhaps the conditions required to produce a taffy-type system may have occurred more often at high redshift, where collisions between gas-rich systems are believed to be much more frequent. In particular, its spectral energy distribution (SED) peaks beyond 100 μm suggesting a huge amount of cold dust in the Taffy system. In this sense, it is crucial to obtain a highly spatially resolved 450 μm SCUBA map and future SIRTF 70 and 160 μm maps in order to fully investigate SED across different regions in the Taffy galaxies. The study of Taffy-like galaxies and a better characterization of their SEDs may thus be relevant to the high-z SIRTF (SED) peaks beyond 100 μm.

It is also interesting to note that the target galaxy is a ring galaxy. Thus, the Taffy system is probably at least a remote relative of galaxies in the “Sacred Mushroom” class of ring galaxies (Arp & Madore 1987). A Sacred Mushroom, e.g., AM 1724–622 (Wallin & Struck-Marcell 1994), is defined by a stem (the intruder) consisting of an edge-on or disrupted companion connected to a ring galaxy forming the cap of the mushroom (the target). An H i image of AM 1724–622 (also known as ESO 138-IG029/30) clearly shows the H i bridge (Hidgon et al. 2001). The intruder’s orientation is different in the Taffy system as compared with the companion of the Sacred Mushroom ring galaxies. The fact that the two galaxies are still in contact implies that the collision is not quite over. Therefore, most of active star-forming regions in the taffy bridge must be fairly young and very recent.

Arp 284 (NGC 7714/15) may provide a better example. The recent high-resolution H i observations (Smith, Struck, & Pogge 1997) show that the bridge gas and H ii regions are both spatially offset from the stellar bridge by a large amount. According to models by Smith & Wallin (1992) and Smith et al. (1997), the bridge may be the result of the combined action of gravitational (tidal bridges) and hydrodynamic (purely gaseous splash bridges) processes. Most ring galaxies like the Cartwheel and VII Zw 466 have gaseous splashes connecting the companion to the target ring galaxy (Hidgon 1996; Appleton, Charmandaris, & Struck 1996). However, the amount of H i in the bridge is small. The large amount of H i gas in the taffy bridge shows how effective these processes can be in some cases.

Although the NRAO VLA Sky Survey (Condon et al. 1998) found only one other taffy system in the nearby universe, taffy phenomena exist in other forms of ISM besides relativistic particles responsible for radio continuum emission. For instance, II Zw 71 (UGC 9562) has been classified as a “probable” polar ring galaxy. However, it is connected to its companion galaxy II Zw 70, a blue compact dwarf galaxy separated by a projected distance of 23 kpc, by a taffy-like H i bridge with no detectable radio continuum emission (Cox et al. 2001). Duc et al. (2000) presented another case (Arp 245) where two galaxies are connected in H i. Quite a few more examples of H i bridges are listed in the H i Rogues Gallery (Hibbard et al. 2001b), e.g., NGC 3424/30 (Nordgren et al. 1997a) and NGC 7125/26 (Nordgren et al. 1997b). It is possible that weak extended radio continuum, which requires much deeper and more sensitive continuum imaging to probe, could exist in these taffy-like H i bridges. Nevertheless, little star formation is occurring in most of the H i bridges since apparently the collision damage to the molecular gas disks is minimal and few GMCs were pulled out of the molecular gas disks. It is worth noting that none of the examples mentioned are LIGs, although most have a large gas reservoir (at least H i).

Other cases exist with radio continuum emission outside of the galaxy disks, but not necessarily located exactly between the merging disks. In NGC 6670 (Wang et al. 2001), a huge H i gas concentration is found between the two merging disks of heavily distorted H i morphology. But the nearly edge-on merging geometry seems to produce an extra-disk H i overlap that is not exactly between the nuclei. Weak radio continuum is also apparent in the H i concentration outside of the disks of NGC 6670. In the Antennae galaxies, the dominant radio continuum emission is also from the overlap region (Neff & Ulvestad 2000; Gao et al. 2001b), which is not exactly between the two nuclei. Also II Zw 96 exhibits dominant radio continuum (Condon et al. 1996; Goldader et al. 1997) where the strongest CO emission is found entirely outside of the two merging stellar disks and also far away from the region between the two galaxies (Gao et al. 2001a). It is difficult to understand how collision/merging could produce so much gas and star formation outside of the disks and offset so far away from the region between the two galaxies. Nonetheless, these systems with extreme offsets in the gas overlap tend to be indeed bona-fide LIGs.

5. CONCLUSIONS

We presented two-field mosaicking CO images of the Taffy system and compared the BIMA CO images with various observations at other wave bands. In particular, we investigated the star formation efficiency (SFE) across the entire system, including the prominent taffy bridge, to identify the starburst sites. The detailed molecular gas distribution and kinematics provide useful constraints on the orbital geometry and impact parameters of the interaction. We summarize our main results as follows:

1. Large amounts of molecular gas were clearly detected throughout the taffy bridge between the two galaxies. The highest CO concentration in the taffy bridge corresponds with the extra-disk Hα source (H ii region) and also with the...
strongest radio continuum source. The molecular gas mass in the taffy bridge amounts to $1.4 \times 10^{10} M_\odot$, using the standard Galactic CO-to-H$_2$ conversion.

2. The overall CO distribution of the entire system, including the taffy bridge, agrees well with that of the radio continuum emission and argues for star formation as the origin of most of the radio continuum emission. We further show that the starburst sites are exclusively in the intruder galaxy UGC 12915 and the adjacent extra-disk H$_2$ source in the taffy bridge. Most of the molecular gas in the taffy bridge is forming into stars at an SFE comparable to that of the target galaxy and similar to that in Galactic disk GMCs. These are derived based on the 20 cm–CO ratio (SFE) maps.

3. Compared with the H i morphology and kinematics, which are strongly distorted owing to the high-speed collision, CO better defines the orbital geometry and impact parameter of the interaction as well as the disk properties. The two spiral disks are clearly counterrotating at speeds above 300 km s$^{-1}$. The intruder’s major axis is more tilted relative to that of its companion than inferred from its optical appearance, which is heavily affected by the dust obscuration and tidal features.

4. The CO observations and a multiwavelength comparison demonstrate that the high-speed counterrotating collision lead to the observed gas (mostly H i, some H$_2$) pileup between the galaxies. The impact parameter must be smaller than the disk radii so that the GMCs in the inner disks and nuclear regions have had more chance to collide during the interaction.

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