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VV 114: Making of an ultraluminous galaxy?

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ABSTRACT

High-resolution ($\theta = 4''.4 \times 3''.1$) CO observations of the IR luminous system VV 114 (IC 1623) using the Owens Valley Millimeter array reveal $5.1 \times 10^{10} M_{\odot}$ of H_2 in a 5.9×3.1 kpc ($15'' \times 8''$) bar with two 4–6 kpc long tails ($D = 80$ Mpc for $H_0 = 75$). The wide separation (6 kpc) of the merging optical galaxies, the extended gas distribution, and the noncircular gas kinematics suggest that VV 114 is in an early stage of a gas-rich merger. The concentration of gas and its dominance of the dynamics in the center of the merging remnant confirms the theory that gas merges before the stars, and the large IR luminosity further implies that the starburst and IR luminous phase can begin long before the majority of gas is concentrated in a compact nuclear source. On the other hand, the fact that *most* ultraluminous IR galaxies have compact nuclear gas complex (like Arp 220) suggests that the IR luminous phase extends well beyond the merger phase. A good correlation in the spatial distribution of CO and 1.4 GHz radio continuum emission is found, and the enhanced nonthermal emission is attributed to magnetic flux freezing in high-density regions.

Subject headings: galaxies: individual (VV 114) — galaxies: interactions — galaxies: starburst — ISM: magnetic fields

1. INTRODUCTION

Many of the infrared luminous galaxies ($L_{\text{IR}} \gtrsim 10^{11} L_{\odot}$) discovered by the *IRAS* survey are merging systems where a large amount of molecular gas is fueling a burst of star formation (Carico et al. 1990; Sanders, Scoville, & Soifer 1991). The mergers of gas-rich systems have been suggested as a mechanism for the formation or fueling of AGNs and even quasars (Norman & Scoville 1988; Sanders et al. 1988), and recent numerical simulations (e.g., Barnes & Hernquist 1991) have strengthened the theoretical understanding of galaxy mergers and induced starbursts. It is now possible to test the predictions of these models by high resolution multifrequency observations of individual systems.

VV 114 is an infrared luminous galaxy ($\log L_{\text{IR}} = 11.62$) whose relative proximity allows a detailed study with a good spatial resolution ($1'' = 390$ pc). The optical and near-IR study by Knop et al. (1994) found widespread star forming activity throughout the system, which consists of two components (VV 114E and VV 114W) separated by ~ 6 kpc in projection. The presence of a large concentration of gas and dust in the nucleus of VV 114E is inferred from the near-IR color (Knop et al. 1994) and by low-resolution CO interferometry (Scoville et al. 1989). The new CO observations reported here find $5.1 \times 10^{10} M_{\odot}$ of molecular gas extended over 6 kpc, peaking near but not on the VV 114E nucleus. Enhancement of the radio continuum emission in the molecular gas by magnetic flux freezing is inferred from the comparison with the optical, infrared, and radio studies. Morphological and kinematic evidence suggests that VV 114 is an early merger system possibly evolving into an ultraluminous system like Arp 220.

2. OBSERVATIONS AND RESULTS

New aperture synthesis CO observations of VV 114 were carried out with the Owens Valley Millimeter array between 1992 April and 1993 June. Baselines extending to 150 m east-west and 140 m north-south resulted in a $4''.4 \times 3''.1$ (P.A. = 3°) synthesized beam. For these observations, there were four 10.4

m diameter telescopes in the array, each equipped with an SIS receiver cooled to 4 K. Typical system temperatures were 300–500 K (DSB). A digital correlator configured with 120×4 MHz channels (10.4 km s^{-1}) covered a total velocity range of 1248 km s^{-1} . The nearby quasar 0048–097 was observed at 25 minute intervals to track the phase and short-term instrument gain, and Uranus ($T_b = 120$ K), 3C 84, and 3C 454.3 were used for the absolute flux calibration. The positional accuracy of the resulting maps is $\sim 0''.5$.

Figure 1 (Plate L6) shows the contours of CO integrated intensity in VV 114 overlaid on an *R*-band CCD image. The extended stellar envelope of this system appears elliptical or box-shaped in the optical light, with a faint tidal tail extending $15'$ to the north, winding counter-clockwise. The CO emission is well centered with respect to this extended stellar distribution. The CO emission is best described as a 5.9×3.1 kpc ($15'' \times 8''$) bar with two 4–6 kpc long tails attached at both ends. The CO bar is aligned with and centered between the two merging optical galaxies. There is a secondary CO peak spatially coincident with the *K* band peak in VV 114E while the brightest CO peak is located $3''$ to the west. There are no optical counterparts to the CO tails.

The total integrated CO flux of 674 Jy km s^{-1} is nearly 1.4 times larger than the single-dish measurement by Sanders et al. (1991). However, the pointing center for the NRAO 12 m observation by Sanders et al. was $25''$ southwest of the CO centroid, and this accounts for the difference within the uncertainty of the measurements. The continuum contribution is negligible since no emission is detected at 24 mJy beam^{-1} (3σ) level in the average map of the line-free channels. Adopting a standard CO-to- H_2 conversion (see Sanders et al.), the total H_2 mass is $5.1 \times 10^{10} M_{\odot}$ and the total gas mass ($H_2 + \text{He}$) is $7.1 \times 10^{10} M_{\odot}$. This is twice as much as Arp 220 (Scoville et al. 1991) and the third most gas-rich, next to IRAS 10214+4724 ($M_{H_2} = 2.0 \times 10^{11} M_{\odot}$; Solomon, Downes, & Radford 1992) and IRAS 14348–1447 ($M_{H_2} = 6.0 \times 10^{10} M_{\odot}$; Sanders et al. 1991). The CO bar contains 84% of the detected CO emission, where the brightest peak ($75 \text{ Jy km s}^{-1} \text{ beam}^{-1}$) corresponds

PLATE L6

FIG. 1.—Integrated CO intensity map in VV 114 is superposed on an *R*-band CCD image that emphasizes the extended faint envelope of stars. The CO contours are 5, 7.5, 10, 15, 25, 32.5, and 62.5 Jy km s⁻¹. At a distance of 80 Mpc ($H_0 = 75$), the synthesized beam of $4''.4 \times 3''.1$ corresponds to 1.7×1.2 kpc. A massive gas complex ($M_{\text{H}_2} = 5.1 \times 10^{10} M_\odot$), described as a central bar and two arms, is well centered with respect to the elliptical or box-shaped extended stellar envelope.

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to a column density of $2.2 \times 10^{23} \text{ cm}^{-2}$ ($A_v \sim 230$). The average gas surface density ($\text{H}_2 + \text{He}$) for the gas bar, $3300 M_\odot \text{ pc}^{-2}$, is 5 times larger than the similar extended component in Arp 220, but it is 2 orders of magnitude smaller than the nuclear component in Arp 220. For contrast to Arp 220, the surface density varies by only a factor of 2 along the entire bar region in VV 114.

The peak flux density observed in the 4 MHz channel maps is $0.43 \text{ Jy beam}^{-1}$, which corresponds to $\Delta T_b = 2.9 \text{ K}$ and Planck brightness temperature of 5.2 K. The brightness temperature of the gas would exceed 30 K if the beam filling factor f is $\lesssim 0.1$. The large ($\gtrsim 10^{10} M_\odot$) molecular gas masses derived for the nuclei of luminous infrared galaxies might be questioned since the unusual conditions in the starburst regions may preclude use of the standard Galactic CO-to- H_2 conversion ratio, but the large extent of the CO emitting region ($\gtrsim 6 \text{ kpc}$) in VV 114 suggests more normal physical conditions. For an assumed beam filling factor of $f = 0.1$ and the inferred average density and temperature (400 cm^{-3} and 30 K), the conversion factor which varies as $n^{1/2}/T_b$ implies that the H_2 mass could be a 35% overestimate.

3. DISCUSSION

3.1. Molecular Gas Distribution and Comparisons to Other Tracers

While the gas distribution is well centered with respect to the extended stellar envelope as seen in Figure 1, the correspondence between the optical and infrared light and CO emission is poor on kpc scales. None of the brightest optical peaks coincide with the brightest CO peaks (Fig. 2a [Pl. L7]). The high extinction associated with the infrared peak VV 114E and low extinction at the brightest optical peak of VV 114W as well as the observed infrared color gradient (Fig. 2c) are consistent with the gas and its associated dust as traced in CO providing the extinction. No optical or infrared features are directly associated with the brightest CO peak found near the center of the CO bar.

One puzzle is the apparent conflict between the large optical extinction inferred from the integrated CO emission ($A_v \gtrsim 100$) and the small extinction inferred from the near IR colors ($A_v \lesssim 10$; see Fig. 3 of Knop et al.). The fact that the infrared peak in VV 114E is seen at all in K band suggests that the mean extinction inferred from the CO observation may be an overestimate. A plausible explanation is that the gas and dust are clumped.

A surprising similarity between the distribution of CO emission and the 1.4 GHz radio continuum emission, including both the bar and tail-like features, is found (Fig. 2b). The 1.4 GHz radio continuum, which is nonthermal synchrotron emission, mimics the CO emission far more closely than the optical or infrared map. Such a correlation has been suggested as evidence for the cosmic-ray heating of molecular clouds, but it is thought to break down at small scales ($\lesssim 1\text{--}2 \text{ kpc}$; see Adler, Allen, & Lo 1991; Allen 1992). Star formation is a common source of CO and radio emission, but the inferred star forming activity from the optical spectroscopy (Knop et al. 1994) is concentrated in the optical galaxies and not in the CO bar. Since the cosmic-ray electron diffusion time from the starburst nuclei to the CO bar ($10^6 \text{ yr } [l/(2 \text{ kpc})][v/(2000 \text{ km s}^{-1})]^{-1}$; see Suchkow, Allen, & Heckman 1993) is much shorter than the lifetime of cosmic-ray electrons by synchrotron loss ($\gtrsim 8 \times 10^7 \text{ yr } [B/(10 \mu\text{G})]^{-2} [E_0/(1 \text{ GeV})]^{-1}$, where E_0 is the initial

energy of the electrons; see Helou & Bica 1993), stronger magnetic field associated with the dense gas may be sufficient to explain the enhanced radio emission in the CO bar even in such a rapidly evolving system. This diffusion scenario is further supported by the increasing $I_{\text{CO}}/I_{1.4 \text{ GHz}}$ ratio towards the center of the CO bar. A similar cosmic ray diffusion model is also suggested for the enhanced radio emission in the atomic gas bridge in the ‘‘Taffy’’ galaxies UGC 12914/5 (Condon et al. 1993). Alternatively, a large optical extinction inferred from the CO flux ($A_v \gtrsim 100$) may be hiding the starburst in the CO bar, but this is inconsistent with the results of the near-IR study (see above).

3.2. Gas Kinematics

The overall velocity gradient associated with the CO emitting gas is along the north-south direction with an average gradient of $0.05 \text{ km s}^{-1} \text{ pc}^{-1}$. The highest velocity gradients and velocity dispersions occur near the mid-point between VV 114E and VV 114W (Fig. 3). Knop et al. (1994) also found the largest equivalent width of the optical emission lines in the same area. Thus, this area probably marks the new dynamic center of the system. The total gas mass of $7.1 \times 10^{10} M_\odot$ traced in CO contributes significantly to the overall mass density in this 6 kpc region; indeed the gas mass fraction there exceeds 90%. Similarly large gas mass fractions are seen in the inner 1–2 kpc regions of most ultraluminous infrared galaxies (see Table 2 of Scoville et al. 1994).

Interpreting the observed velocity gradient as pure rotation faces a number of obstacles. First of all, the iso-velocity contours are highly irregular, and noncircular components in the velocity field must be significant. If the line of nodes in the iso-velocity contours is interpreted as that of rotation, the major axis of the gas orbits should lie along the north-south direction. However, the orientation of the CO distribution is instead in the east-west direction. The long-slit optical spectroscopy by Knop et al. (1994) found little velocity difference between VV 114E and VV 114W and no evidence for relative orbital motion. Position-velocity (‘‘ l - v ’’) plots along the kinematic major axis bisecting the central CO bar reveal that the observed velocity gradient is instead produced by two kinematically distinct components slightly offset in position. The l - v plots along the lengths of the CO tails show that they each have a single physical component, with their kinematics mirroring each other as if responding to a common potential. In summary, the absence of clear rotational signature, the global coherence in the kinematics, and the large velocity gradient along the arms suggest that radial motions of infall (or outflow) dominate the gas kinematics as found in the early time sequences of the merger simulations (see Barnes & Hernquist 1991). The near-infrared image of VV 114E resembles a disk seen nearly edge-on, suggestive of an intact compact inner disk of a merging galaxy, but neither an enhanced velocity dispersion nor a rotation-like velocity gradient is found.

3.3. Merger and IR Luminous Phase

The first clue suggesting that VV 114 is an early merger system is the wide separation (6 kpc in projection) of the main optical/IR nuclei (Figs. 1 and 2). In comparison, advanced merger systems such as Arp 220 often possess close double nuclei, generally separated by less than 1 kpc. The optical spectra of the bright optical knots in VV 114W are characteristic of starbursts or H II regions, and no associated radio point source is found (Knop et al. 1994; Condon et al. 1990). VV

FIG. 2.—Integrated CO intensity (a, c) and 1.49 GHz radio continuum (b) ($\theta = 2''.1$ by Condon et al. 1990) are shown in contours superposed on an *R*-band CCD image (a, b) and *H*–*K* color map by Knop et al. (1994). The CO and radio emission are remarkably similar and may be explained by enhanced magnetic field in the dense gas traced by CO (see § 3.1). The CO emission is not well correlated with the optical or infrared features, however. The *H*–*K* color gradient seen in (c) is suggestive that the gas and dust associated with the CO provides the extinction.

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FIG. 3.—Mean velocity contours are superposed on the second moment (velocity dispersion) map in gray scale. The velocities are marked in km s^{-1} . Both the largest velocity gradient and largest velocity dispersion occur near the center of the gas bar, and this region may mark the new dynamical center for the merger remnant.

114E has a double peak both at K band and at 8.44 GHz (Condon et al. 1991), and at least one AGN may already be lurking in this system. On the other hand, the recent near-infrared imaging and spectroscopic study by Doyon et al. (1994) suggests that there is only one nucleus in VV 114E and that it is probably a starburst.

Our CO observations find an extended molecular gas distribution with no dominant core while the CO emission in more advanced merger systems such as Arp 220 and Mrk 231 is highly concentrated in the inner 1 kpc region (Scoville et al. 1991; Bryant & Scoville 1994). In fact, Mrk 273 (Yun et al. in preparation) and NGC 7674 (Bryant & Scoville 1994) are the only other known luminous infrared galaxies where the majority of the molecular gas extends significantly outside the nuclear starburst region. The observed gas kinematics (§ 3.2) suggests that the gas has not yet settled into a regular orbital motion in the central potential. In the numerical simulation of gas-rich disk mergers by Barnes & Hernquist (1991), nearly all gas kinetic energy and angular momentum are dissipated in $4\text{--}5 \times 10^8$ years from the initial collision via radiative cooling and gravitational torques. By 8×10^8 years after the collision, $\sim 60\%$ of all gas is found concentrated in the inner 200 pc region, and the stellar component forms a smooth and regular envelope following a de Vaucouleurs law as in Arp 220 (Scoville et al. 1991; Wright et al. 1990). Our analysis of the R -band CCD image of VV 114 finds that the bright optical knots in the inner 6 kpc region dominate the optical light distribution and the stellar envelope has not settled into an $r^{1/4}$

distribution yet. The CO and stellar distributions as well as the gas kinematics suggest that the best estimate for the collision that produced VV 114 may be $3\text{--}4 \times 10^8$ years old in the framework of this numerical model. If the merger interpretation is correct, this system may eventually evolve to resemble Arp 220—compact double nuclei with $2 \times 10^{10} M_{\odot}$ of molecular gas concentrated in the central 600 pc fueling a massive starburst.

An interesting consequence of finding still merging systems with on-going starburst is the insight they provide on the onset of the starburst and the duration of the IR luminous phase. The CO emission extends outside the nuclear region for some of IR luminous galaxies observed at high spatial resolution (see above and Scoville et al. 1994), and the *starburst phase must begin well before the majority of the gas is channeled into the nuclear region*. On the other hand, some $\frac{2}{3}$ of all the IR luminous systems may be categorized as massive nuclear concentrations, and this suggests that the *IR luminous phase extends well beyond the merger phase*—longer than 8×10^8 years from the initial collision in Barnes & Hernquist model. Increasing luminosity with sustained starbursts results in an observational bias towards the older and more luminous systems, and still luminous postburst systems may further skew the statistics (see Scoville & Soifer 1990). An alternative interpretation is that the IR luminous systems with extended gas distributions belong to a special class of merger remnants whose gas somehow did not shed all its angular momentum after the initial collision.

4. SUMMARY

A massive molecular gas complex 6 kpc in diameter with $5.1 \times 10^{10} M_{\odot}$ is found in the center of an early merger system VV 114. The molecular gas forms a bar and two tail-like features, and noncircular motion dominates gas kinematics. While the gas distribution is exceptionally extended for an infrared luminous galaxy, its stellar distribution is far from reaching the advanced merger state. There is already a high rate of star forming activity evidenced by the high IR luminosity, and the continuing evolution and starburst fueled by an enormous gas reserve suggest that VV 114 may one day become an ultraluminous galaxy like Arp 220. And the pres-

ence of systems with extended molecular gas distribution such as VV 114 suggests that the IR luminous phase begins early in the process of galaxy mergers, but the dominance of IR luminous galaxies with a compact CO distribution like Arp 220 suggests that the IR luminous phase continues well beyond the merger phase. The concentration of gas and its dominance of the dynamics in the center of the merging remnant confirms the theory that gas merges before the stars.

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