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AN EXTENDED MOLECULAR GAS DISTRIBUTION IN MARKARIAN 273 AND MERGER-LUMINOSITY EVOLUTION

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ABSTRACT

We present the first interferometric measurement of CO emission ($\theta \sim 2''$) from the ultraluminous infrared galaxy Mrk 273. A total H_2 mass of $3.6 \times 10^{10} M_\odot$ is inferred from the CO observations, half of which belongs to an extended component with deconvolved size 5.1×2.5 kpc. In addition, an unresolved molecular gas complex is found to be coincident with the optical nucleus. The inferred H_2 mass, size ($R \sim 380$ pc), and mean surface mass density ($\Sigma_{H_2} \geq 4 \times 10^4 M_\odot \text{pc}^{-3}$) of this complex, as well as the IR luminosity, are very similar to those of Arp 220. The gas in the extended component shows a rotational velocity gradient with the kinematic major axis aligned with the position angle of the two nuclei seen in the near-infrared. The extended molecular gas distribution and separation of the two nuclei suggest that Mrk 273 is a young merger system. The CO emission appears confined to the edge-on system, and the second merger progenitor may have been gas-poor or may have had its gas transferred to the companion during the merger. The comparison of the physical properties of Mrk 273 with two other similarly gas-rich IR luminous systems, VV 114 and Arp 220, finds a monotonic increase in average gas surface density and IR luminosity efficiency (L_{IR}/M_{H_2}) with decreasing projected separation of the stellar nuclei. We find that now all four nearest ultraluminous systems observed at high spatial resolution (Arp 220, Arp 299, Mrk 231, and Mrk 273) are associated with central mass surface density in excess of $10^4 M_\odot \text{pc}^{-2}$.

Subject headings: galaxies: individual (Markarian 273) — galaxies: interactions — galaxies: starburst

1. INTRODUCTION

Mrk 273 is an ultraluminous infrared galaxy detected in the *IRAS* survey with $L_{\text{IR}} = 1.1 \times 10^{12} L_\odot$ (Sanders, Scoville, & Soifer 1991). The optical image shows a bright, thin tidal tail extending $20''$ to the south of the galaxy as well as a faint fanlike plume to the north, suggestive of two disk galaxies interacting or merging (Vorontsov-Velyaminov 1977; Sanders et al. 1988; see Fig. 1 [Pl. L6]). Two Seyfert nuclei separated by $1''$ (0.7 kpc at 151 Mpc) are seen in near-IR observations, and the brighter (northern) $2 \mu\text{m}$ nucleus coincides with the optical nucleus (Mazzarella & Boroson 1993; Majewski et al. 1993; Zhou, Wynn-Williams, & Sanders 1993). Radio continuum observations by Ulvestad & Wilson (1984) found several associated radio sources, the brightest of which appears to coincide with the optical nucleus (Majewski et al. 1993). Mrk 273 also exhibits OH megamaser emission, but the $1''$ resolution VLA observations by Schmelz, Baan, & Haschick (1987) could not resolve the OH emission distribution. Subsequent $1''$ resolution H I absorption observations partially resolved a disklike structure with an inferred radius of 106 pc (Schmelz, Baan, & Haschick 1988).

We present the $2''$ resolution aperture synthesis CO observations of Mrk 273 using the Owens Valley Millimeter Array. The molecular gas distribution in Mrk 273 consists of an extended component with deconvolved size of 5.1×2.5 kpc as well as a massive, compact component similar to that in Arp 220 (Scoville et al. 1991; Scoville, Yun, & Bryant 1995). The correlation between the IR luminosity and molecular gas properties is discussed in the context of merger and luminosity evolution.

2. OBSERVATIONS AND RESULTS

Aperture synthesis CO observations of Mrk 273 were carried out with the Owens Valley Millimeter Array between 1992 January and May. Baselines extending to 200 m east-west and 180 m north-south resulted in a $2''.2 \times 2''.3$ (P.A. = 6°) synthesized beam. For these observations, there were three 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 (single sideband) at 111 GHz. A digital correlator configured with 120×4 MHz channels (11.2 km s^{-1}) covered a total velocity range of 1340 km s^{-1} . The nearby quasar $1418+546$ was observed at 25 minute intervals to track the phase and short-term instrument gain, and Uranus ($T_B = 120$ K), Neptune ($T_B = 115$ K), $3C 273$, and $3C 454.3$ were used for the absolute flux calibration. The uncertainty in the flux measurements is about 10% , and the positional accuracy of the resulting maps is better than $\sim 0''.4$.

Figure 1 shows the contours of CO-integrated intensity in Mrk 273 overlaid on an *R*-band CCD image. The CO contours closely follow the optical light. The deconvolved size of the CO emitting region is $6''.9 \times 3''.4$ (5.1×2.5 kpc; $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$), extended in the north-south direction. The molecular gas distribution consists of a compact nuclear component and an extended component as described further below, each with nearly the same CO luminosity (see Table 1). The total integrated CO line flux in the map is 133 Jy km s^{-1} . Adopting a standard CO-to- H_2 conversion (see Sanders et al. 1991), the total inferred H_2 mass is $3.6 \times 10^{10} M_\odot$, and the total gas mass ($H_2 + \text{He}$) is $5.0 \times 10^{10} M_\odot$ —placing Mrk 273 among the most gas-rich galaxies in the local universe.

The peak of the CO emission coincides with the optical

TABLE 1
OBSERVATIONAL SUMMARY

Parameter	Mrk 273
R.A. (1950) ^a	13 ^h 42 ^m 51 ^s .706
Decl. (1950) ^a	+56°08′14″35
Distance ^b	151 Mpc (1″ = 0.73 kpc)
L_{IR}^c	$1.1 \times 10^{12} L_{\odot}$
$\langle cz \rangle_{\text{CO}}$	11,325 km s ⁻¹
ΔV_{CO} (FWHM)	448 km s ⁻¹
$N_{\text{H}_2, \text{peak}}^d$	$4.6 \times 10^{23} \text{ cm}^{-2}$
Deconvolved size	5.1 × 2.5 kpc (P.A. = 179°)
$S_{\text{CO}} \Delta V$ (Jy km s ⁻¹):	
Nuclear	62.2
Extended	70.8
Total	133.0
M_{H_2} ($10^{10} M_{\odot}$): ^d	
Nuclear	1.7
Extended	1.9
Total	3.6
$\Sigma_0(\text{H}_2)$ ($M_{\odot} \text{ pc}^{-2}$):	
Nuclear, average over the beam	5500
Nuclear, if $R = 380^e$ pc	37,500
Extended	1300

^a Radio continuum peak position from Ulvestad & Wilson 1984.

^b Assumes $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

^c From Sanders et al. 1991.

^d Assumes $\alpha = 3 \times 10^{20} \text{ cm}^{-2} (\text{K km s}^{-1})^{-1}$ (see Sanders et al. 1991).

^e Dynamical size (see § 3.1).

nucleus, and the integrated CO flux at the peak, 69.2 Jy km s⁻¹ beam⁻¹, implies a mean H₂ column density of $4.6 \times 10^{23} \text{ cm}^{-2}$ ($A_V \sim 480$). The southern *K*-band nucleus has $H - K$ color 0.3 mag redder than the brighter northern *K*-band nucleus (L. Armus, private communication), possibly due to higher reddening and consistent with a geometry in which the southern nucleus lies behind the bulk of the gas and dust. The peak flux density observed in the 16 MHz (45 km s⁻¹) channel maps is 184 mJy beam⁻¹, which corresponds to $\Delta T_b = 3.6 \text{ K}$ and an absolute Planck brightness temperature of 5.9 K. If the size of the unresolved nuclear CO emission region is comparable to that of Arp 220 ($770 \times 470 \text{ pc}$; Scoville et al. 1995), then the line brightness excess would be about 30 K, consistent with the dust temperature inferred from the *IRAS* measurements.

3. DISCUSSIONS

3.1. Molecular Gas Distribution and Kinematics

The CO distribution in Mrk 273 has an extended component with deconvolved size $5.1 \times 2.5 \text{ kpc}$ (P.A. = 179°) and an unresolved nuclear component, each containing about $2 \times 10^{10} M_{\odot}$ of molecular gas (see Table 1). The extended nature of the molecular gas distribution in Mrk 273 is somewhat surprising, since previous interferometric observations found unresolved compact gas distribution in most luminous infrared galaxies at 6″ resolution (e.g., Scoville et al. 1989). The discovery of the extended component in Mrk 273 is in part due to the high spatial resolution achieved by this study. In the nearest ultraluminous system Arp 299, three separate molecular gas complexes were found by Sargent & Scoville (1991), and the new 2″ resolution CO observations by Bryant & Scoville (1995) have resolved molecular gas structure and kinematics in a large number of gas-rich IR luminous systems identified by Sanders et al. (1991). The most spectacular example of massive extended molecular gas complex is found in VV 114, which has a $5.9 \times 3.1 \text{ kpc}$ molecular gas bar with

$5.1 \times 10^{10} M_{\odot}$ of H₂ connecting the two merging nuclei, separated by 6 kpc (Yun, Scoville, & Knop 1994).

The unresolved molecular gas component in Mrk 273 spatially coincides with the northern *K*-band nucleus, which is also the optical nucleus. If the gas mass dominates the dynamical mass in the nuclear region (Downes, Solomon, & Radford 1993, Bryant & Scoville 1995), the observed line width of 450 km s⁻¹ then implies a radius of 380 pc for the nuclear gas complex. This is nearly identical to the size of the molecular gas disk surrounding the two nuclei in Arp 220 (Scoville et al. 1995). The inferred H₂ mass for the compact component is also comparable to the molecular disk in Arp 220. Hence, along with its large IR luminosity, Mrk 273 closely resembles Arp 220 in its nuclear properties.

The CO emission appears to be associated with only the system seen edge-on, while the absence of CO counterparts for the southwest optical extension and the southern *K*-band nucleus suggests that the second progenitor may have been gas-poor or may have had its gas transferred to the (possibly more massive) companion. The observed differences in CO and optical morphology may be explained in part by the difference in the dynamical evolution between stars and gas in the merger remnant as well as by possible dust extinction. On the other hand, the recent observations suggest that mergers involving only one gas-rich system can also initiate starburst activity as in Arp 220 (Yun & Hibbard 1995).

A position-velocity plot along the morphological major axis (north-south) does not show any clear kinematic pattern. The intensity-weighted mean velocity (“first moment”) map shows a systematic velocity gradient at a position angle of 30°, which has no particular significance in the CO distribution but is coincident with the position angle of the two *K*-band nuclei. The large line width ($\Delta V_{\text{FWHM}} = 450 \text{ km s}^{-1}$) associated with the nuclear component dominates the position-velocity plot along this kinematic major axis (see Fig. 2 [Pl. L7]). The gas in the extended component appears at less extreme velocities and displays an organized rotation-like kinematic signature. The alignment of the two nuclei with the kinematic major axis suggests that the extended molecular gas may be currently settling into the new central potential of the merger remnant. If the merger is still ongoing, then both the gas distribution and the kinematics observed should be transient in nature and are not expected to correspond closely to each other. If the system is not dynamically relaxed yet, then any organized motion such as the suggested rotation may be fortuitous. On the other hand, the alignment between the kinematic major axis and the fundamental plane of the new potential is expected to occur within a few dynamical times, and this may already be the case in Mrk 273.

3.2. Gas-rich Merger and Evolution of IR Luminous Phase

Merging two or more galaxies is clearly an important physical process for forming ultraluminous ($L_{\text{IR}} > 10^{12} L_{\odot}$) galaxies in the majority of (and possibly in all) cases. At least six of the 10 nearest ultraluminous galaxies are clear merger remnants with close double nuclei (Majewski et al. 1993). Numerical models of gas-rich mergers by Barnes & Hernquist (1991) offer a plausible picture of how the high gas concentrations found in the centers of these galaxies may be achieved. Mihos & Hernquist (1995) suggest that the presence of massive bulges may delay the infall of disk gas into the new

TABLE 2

SUGGESTED MERGER SEQUENCE ALONG THE BARNES & HERNQUIST MODEL

Parameter	VV 114 ^a	Mrk 273	Arp 220 ^b
Separation (kpc)	6	0.7	0.35
L_{IR} ($10^{11} L_{\odot}$)	4	11	16
M_{H_2} ($10^{10} M_{\odot}$)	5.1	3.6	2.0
$L_{\text{IR}}/M_{\text{H}_2}$ ($L_{\odot}/M_{\odot}$)	7.8	31	80
Σ_{H_2} ($10^3 M_{\odot}$)	3.3	5.5 (38 ^c)	80

^a Yun, Scoville, & Knop 1994.^b Scoville, Yun, & Bryant 1995.^c Unresolved component, assuming $R = 380$ pc (see § 3.1).

central potential until the merger of the nuclei themselves occurs.

The presence of both compact and extended gas distributions seen in Mrk 273 is probably an intermediate stage in the evolution of merging galaxies. The comparison of gas distribution and physical characteristics of Mrk 273 with two other gas-rich systems VV 114 (an ongoing merger; Yun et al. 1994) and Arp 220 (the prototypical ultraluminous system) provides a picture consistent with the merger scenario of Barnes & Hernquist (1991) (and subsequent luminosity evolution; see Table 2). The suggested sequence of “VV 114 $\rightarrow$ Mrk 273 $\rightarrow$ Arp 220” is *purely based on the apparent separations of the two nuclei*, and both the IR luminosity and the luminosity efficiency ($L_{\text{IR}}/M_{\text{H}_2}$) increase monotonically with decreasing nuclear separation along this sequence. The gas mass surface density Σ_{H_2} increases dramatically with decreasing separation of stellar nuclei, while the total H_2 mass actually *decreases*. The correlation between IR luminosity efficiency and gas density has been suggested previously (Scoville et al. 1991). The absence of a similar correlation between the IR luminosity and the total H_2 mass among these three galaxies is at first somewhat surprising; however, this may simply mean that merger evolution is more important in the luminosity evolution than the initial total gas content. One may interpret the apparent decrease in the total H_2

gas mass as a sign of gas depletion, but the current gas content obviously also depends on the initial gas contents of the progenitors, which were previously not identical.

The importance of high central gas mass density for achieving high total luminosity (starburst or AGN) is best evidenced by the fact that all ultraluminous systems ($L_{\text{IR}} > 10^{12} L_{\odot}$) observed at high spatial resolution have inferred Σ_{H_2} exceeding $10^4 M_{\odot} \text{pc}^{-2}$: Arp 220 ($8 \times 10^4 M_{\odot} \text{pc}^{-2}$; Scoville et al. 1991, 1995), Mrk 273 ($\geq 4 \times 10^4 M_{\odot} \text{pc}^{-2}$; this study), IC 694 ($\geq 3 \times 10^4 M_{\odot} \text{pc}^{-2}$; Sargent & Scoville 1991), and Mrk 231 ($3 \times 10^4 M_{\odot} \text{pc}^{-2}$; Bryant & Scoville 1995). These are two orders of magnitude larger than the typical values seen in the centers of normal disk galaxies. The fact that more gas-rich but less condensed systems like VV 114 have not achieved similarly high luminosity lends strong support for this argument. It is worth noting that all these ultraluminous galaxies have central gas mass densities exceeding $10^2 M_{\odot} \text{pc}^{-3}$, comparable to the stellar mass densities in the cores of giant ellipticals and in support of their formation by merger-induced dissipative collapse (cf. Kormendy & Sanders 1992).

In summary, the luminosity evolution for the IR luminous galaxies appears closely tied to the merger evolution, best indicated by the separation of the two nuclei and the subsequent rise in the central gas mass density. Large total H_2 mass ($\geq 10^{10} M_{\odot}$) is apparently an essential requirement in achieving the extreme IR luminosities associated with these galaxies. In addition, the new high-resolution observations suggest that high central gas mass density may ultimately determine the IR luminosity and associated activity. Clearly, a much larger sample of gas-rich merging systems should be examined to generalize these conclusions.

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FIG. 1.—R-band CCD image of Mrk 273 (kindly provided to us by L. Armus) is presented in contours in the left-hand panel to show the two stellar tails and a tidal plume, while the integrated CO intensity map is shown in contours over the gray-scale map of the optical image in the right-hand panel. Tail A likely originates from a disk system seen edge-on, while tail B and the tidal plume must originate from the second, more face-on system (see Fig. 22 of Toomre & Toomre 1972 for an illustrative model of the tidal interaction that is likely involved in this system). The nucleus of the face-on system is not apparent in the optical image, but its presence is confirmed by the spectroscopic study (Seyfert 2) and by K-band imaging (Mazzarella & Boroson 1993; Majewski et al. 1993; Zhou et al. 1993). The CO contours correspond to H_2 column densities of $1.2, 1.8, 2.4, 3.6, 6, 9, 15, 24$, and $38 \text{ times } 10^{22} \text{ H}_2 \text{ cm}^{-2}$. At a distance of 151 Mpc ($H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$), the synthesized beam of 2.2×2.3 corresponds to $1.6 \times 1.7 \text{ kpc}$. The CO contours generally follow the optical light distribution of the edge-on system, while the lack of associated CO emission with the optical extension to the southwest and the southern K-band nucleus suggests that the second progenitor may be gas-poor or that the gas has preferentially transferred to the first (possibly more massive) galaxy.

FIG. 2.—CO position-velocity plot along the kinematic major axis (P.A. = 30°). The velocity offsets are with respect to $cz = 11,325 \text{ km s}^{-1}$, and the contours correspond to -12, -8, 8, 12, 16, 24, 40, 60, and 100 mJy beam⁻¹. As in many disk galaxies, the largest line width is found at the nucleus, and the kinematic signature of the extended component suggests a disk rotation.

YUN & SCOVILLE (see 451, L46)