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CO-Line Emission from the Clumpy Irregular Galaxy Markarian 297

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^{12}CO ($J = 1-0$)-line emission has been detected in the direction of the clumpy irregular galaxy Mrk 297 (Arp 209, NGC 6052). The CO emission region is compact, associated with the brightest optical knots and slightly extended toward the east. The estimated molecular mass is $\sim 5 \times 10^9 M_{\odot}$, comparable to the H I mass. The FIR-to-CO luminosity ratio suggests that this galaxy is a typical starburster. The kinematics of the CO and H I gases are discussed based on a radial-penetration encounter model of two galaxies on the line of sight. A mildly disturbed component, which is seen nearly face-on, contains both H I and molecular gas, and the tidal disturbance may have caused the active star formation in dense molecular clouds. On the other hand, the more disturbed edge-on component contains much H I, but little molecular gas, which may have become dissociated during a tidal encounter.

Key words: CO emission; Galaxies, interacting; Molecular hydrogen; Starburst; Star formation.

1. Introduction

Galaxies of irregular morphology having clumpy giant knots of H II regions are known as clumpy irregular galaxies, and have been shown to be in an active phase of star formation (e.g., Heidmann 1987). The Markarian galaxy Mrk 297 (= Arp 209 = NGC 6052) is a typical example of this type. Due to its very peculiar morphology (Arp 1966) and to the large extent of the region containing H II clumps (Hecquet et al. 1987; Maehara et al. 1988; Taniguchi and Tamura 1987), it is still controversial whether Mrk 297 should be classified as a starburst galaxy comparable to M82.

The usual type starburst has come to be understood as the result of rapid accretion of molecular gas orbiting in a distorted potential, which has been primarily caused via a galaxy-galaxy interaction (e.g., Noguchi 1988). In fact, many bursting galaxies are interacting/merging systems. Alloin and Duflot (1979) have suggested that Mrk 297 may be an interacting system, and Schweizer (1983) has classified it to be a merger. Recently, Taniguchi and Noguchi (1990) showed by a numerical simulation that the morphological properties can be well explained by a radial-penetration collision of two spiral galaxies nearly along the line of sight.

In order to clarify whether Mrk 297 should be classified as a starburst galaxy, the content and behavior of the molecular gas should give an important clue. However, there has been no report concerning the detection of CO emission (Gordon et al. 1982; Sofue et al. 1986). From this absence of detection, which was due to both a poor pointing accuracy and to a worse receiving system of the telescope at that time, Sofue et al. (1986) gave only an upper limit to the CO line intensity. They argued that Mrk 297 may be in a phase in which the molecular gas has been exhausted by active star formation.

In this *Letter* we revisit this problem: if this galaxy really contains a smaller amount of CO gas than a usual starburster, or if detection is possible with our improved telescope today, we wish to know what distribution and behavior the galaxy shows, compared to other gas-rich starbursters.

2. Observations

Observations of the ^{12}CO ($J = 1 - 0$) line of Mrk 297 were made on February 26 and 27, 1990 using the 45-m telescope of the Nobeyama Radio Observatory during the course of a survey of Arp's interacting galaxies. Observational details with a full description of the survey will be reported in a separate paper. The antenna had a HPBW of 17$''$, which corresponds to a linear diameter of 5.3 kpc at a distance of 64 Mpc for a Hubble constant of 75 km s^{-1} Mpc^{-1}. The pointing accuracy was better than $\pm 3''$ throughout the observations. We used a cooled Schottky-barrier diode mixer receiver combined with a 2048-channel acousto-optical spectrometer with a velocity coverage of 650 km s^{-1}. After binding up every 32 to 64 channels in order to increase the signal-to-noise ratio, we obtained spectra with a velocity resolution of 10 to 20 km s^{-1}. The system noise temperature, including the atmospheric effect and ohmic losses, was 650 to 700 K.

The central position was observed for one hour with simple on-off position switching; the on-source integration time was 25 min. For another 5 positions around the

Table 1. Observational parameters for Mrk 297 (Arp 209 = NGC 6052).

Adopted center position (0″, 0″)		
R.A.$_{1950}$	$16^h03^m01^s.2$	
Decl.$_{1950}$	$20°40'43''$	
V_{LSR}	4710 km s^{-1}	
Distance	64 Mpc	$H = 75$ km s^{-1} Mpc^{-1}
Peak $T_A^*(T_{mb})$	100 (230) mK	
I_{CO} at (0″, 0″)	23.3 ± 1.0 K km s^{-1}	
L_{CO}	$8.9 \pm 1 \times 10^8$ K km s^{-1} pc^2	
L_{FIR}	6.4×10^{10} $L_⊙$	Heidmann (1987)
M_{H_2}	5.1×10^9 $M_⊙$	
$M_{H I}$	1.2×10^{10} $M_⊙$	Maehara et al. (1988)

center at a 15″ spacing we used a multi-on-off switching mode and spent a total of 2 hr; the on-source integration time per point was 15 min. The resultant spectrum of 10 km s^{-1} velocity resolution for the central region and those with 20 km s^{-1} resolution for the other region had an rms noise of $\Delta T_A^* \simeq 10$ mK. Table 1 summarizes the observational parameters, and figure 1 shows the observed points and beamwidth superposed on an optical photograph as reproduced from Arp (1966).

3. Results

The obtained CO spectra at a velocity resolution of 20 km s^{-1} are shown in figure 1. The spectrum at the center shows emission as strong as T_A^*= 100 mK. The CO emission was also detected at 15″E and at 15″N, while no significant emission was seen at 30″E or toward 15″W and 15″S. Several peaks appearing in the spectrum at 30″E are not significant when compared to the large rms noise and baseline wobbling in this spectrum. From the pointing accuracy and a beamwidth of 17″, we may conclude that the CO emission region is mostly confined to within the central region of 5 kpc diameter, though slightly extended toward the north and east.

The velocity profiles at the center and at 15″N are nearly Gaussian shaped. The velocity width at half maximum at the center is about 140 km s^{-1} and that at zero power is about 190 km s^{-1}. The lower-left panel of figure 1 shows the spectrum at a resolution of 10 km s^{-1}. In this spectrum we can recognize three peaks, at V_{LSR}= 4630, 4690, and 4740 km s^{-1}. The profile at 15″E looks wider and flat-topped, and has a velocity width of 230 km s^{-1}. The mean velocity is red-shifted with respect to the center by about 60 km s^{-1}.

The integrated CO intensity is given by $I_{CO} = \int T_A^* dv \eta_b^{-1}$ with $\eta_b = 0.43$ being the main beam efficiency. We obtained $I_{CO} = 23.3 \pm 1.0$, 12.6 ± 0.4, and 5.1 ± 1.7 K km s^{-1}, respectively, at the center, at 15″N, and at 15″E. From the detected values of I_{CO} we estimated the total CO luminosity to be $L_{CO} = (8.9 \pm 1) \times 10^8$ K km s^{-1} pc^2. Then, the total mass of hydrogen molecules can be derived using an empirical relation given by Scoville et al. (1987); we obtained $M_{H_2} \sim 5.1 \times 10^9 M_⊙$.

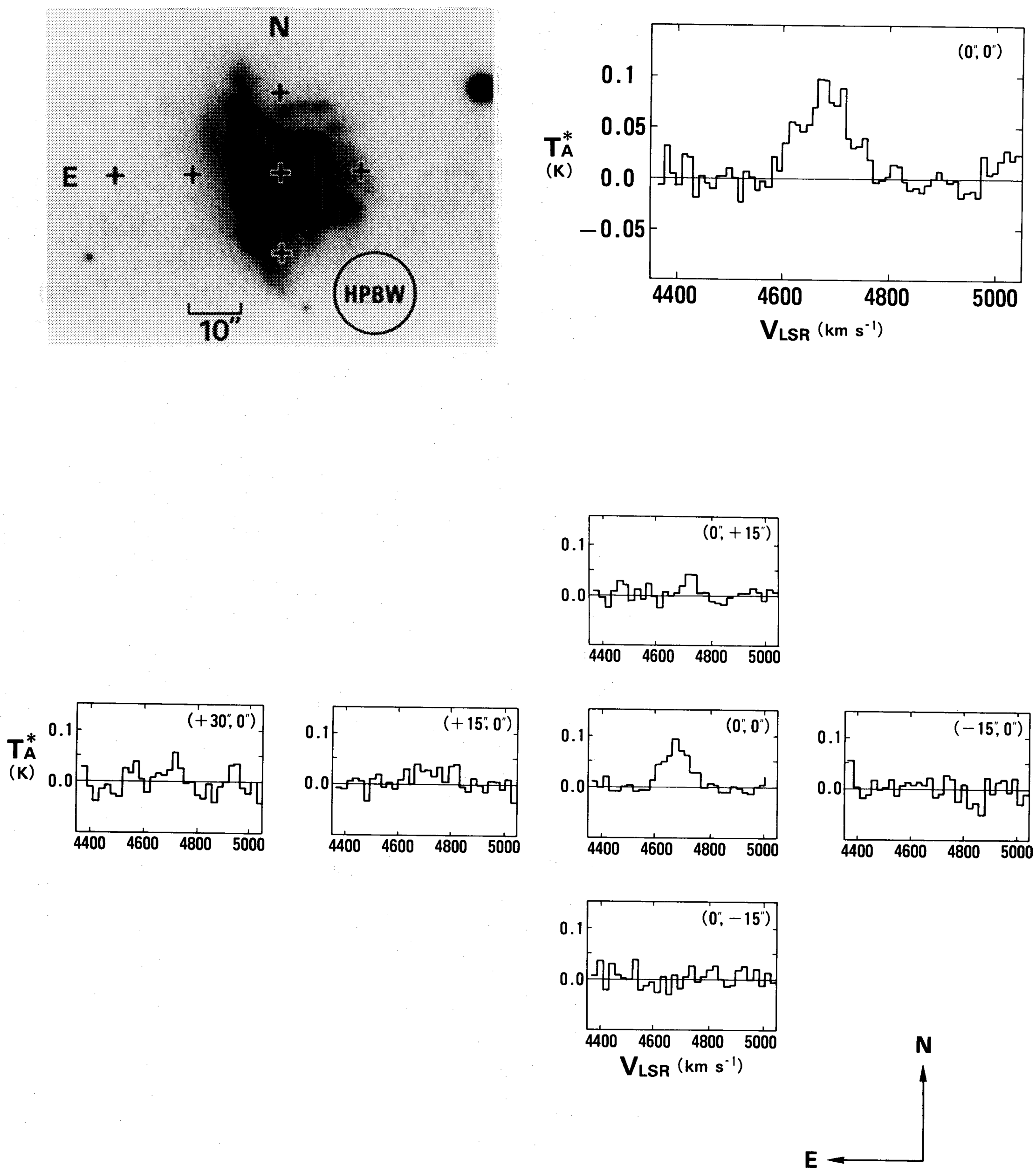

Fig. 1. ^{12}CO ($J = 1-0$) line profiles for Mrk 297 (Arp 209) with a velocity resolution of ΔV = 20 km s^{-1} are shown for the six positions. The upper-right panel shows a higher-resolution (ΔV = 10 km s^{-1}) CO spectrum for the center position. The upper-left panel shows a photograph of Mrk 297, as reproduced from Arp (1966). The crosses indicate observed positions. The center position (0″, 0″) is at the densest part in this photograph.

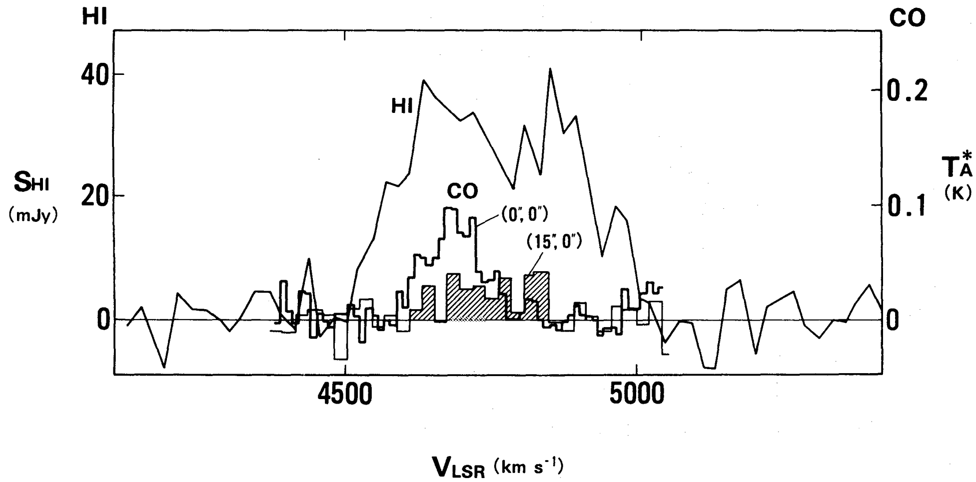

Fig. 2. Comparison of the CO profiles at the center and at 15″E for Mrk 297 with an H I profile (Maehara et al. 1988). The CO profile at (0″, 0″) coincides with the bluer H I peak.

4. Discussion

Optically, Mrk 297 contains a group of tens of giant H II regions each of the size ~ 100 pc, widely spread within the central 3-kpc region (Heidmann 1987; Hecquet et al. 1987; Maehara et al. 1988). The velocity dispersion of individual clumps is twice that of nearby giant H II regions (Taniguchi and Tamura 1987). The far-infrared luminosity of this galaxy is as large as $8 \times 10^{10} L_\odot$ (Heidmann 1987), which puts Mrk 297 among starburst galaxies (Telesco 1988). The FIR-to-CO luminosity ratio of $L_{\rm FIR}/L_{\rm CO} \sim 90\ L_\odot/({\rm K\ km\ s^{-1}\ pc^2})$ is an order of magnitude greater than that of normal spiral galaxies [$\sim 20\ L_\odot/({\rm K\ km\ s^{-1}\ pc^2})$] and is comparable to that of bursters like Arp 220 and NGC 6240 [~ 200 and 100 $L_\odot/({\rm K\ km\ s^{-1}\ pc^2})$, respectively; Sanders and Mirabel 1985].

The velocity structures for the H I and CO gases are remarkably different from each other. In figure 2 we compare our CO profiles at the center and at 15″E with an H I profile from a lower-resolution ($4' \times 22'$) observation (Maehara et al. 1988). The H I profile comprises two peaks, one centered at $V_{\rm LSR} = 4660$ km s^{-1}, and the other at 4880 km s^{-1}. The bluer (smaller velocity) H I peak coincides with the CO peak at the center. On the other hand, the redder H I peak has a less-clear counterpart in CO emission, while a redder hump at about $V_{\rm LSR} = 4800$ km s^{-1} in the 15″E profile seems to be correlated with this redder H I peak. The large H I velocity dispersion of 500 km s^{-1} and double peaks at a velocity separation as large as ~220 km s^{-1} for the H I gas (Maehara et al. 1988) may be due to the fact that we are observing two interacting galaxies and their tidal tails as a whole.

Of the total H I mass ($M_{\rm H\,I} \sim 1.2 \times 10^{10} M_\odot$; Maehara et al. 1988), about half, $\sim 6 \times 10^9 M_\odot$, is contained in this bluer component. Of the total H_2 mass ($M_{\rm H_2}$ ~

$5.1\times10^9 M_{\odot}$), about 90 %, or $\sim 4.5\times10^9 M_{\odot}$, is associated with the blue H I component. Therefore, the molecular-to-atomic hydrogen mass ratio in the blue component is about unity, which is not significantly different from that for normal galaxies. On the other hand, the redder H I component, the H I mass of which is also $\sim 6\times10^9 M_{\odot}$, is associated with a smaller amount of molecular gas, $M_{H_2} \sim 5\times10^8 M_{\odot}$. This yields a smaller molecular-to-atomic hydrogen mass ratio of ~ 0.1.

According to a radial-penetration model of Taniguchi and Noguchi (1990), Mrk 297 is a superposition of two galaxies on the line of sight after a tidal penetration. The radially penetrated (more disturbed) galaxy, which is nearly edge-on from our line of sight, is observed as the eastern "wing"-shaped ridge elongated in the NS direction on the photograph. The other galaxy, the "intruder," is nearly face-on and has experienced an axial penetration by the edge-on galaxy. This face-on galaxy experienced a ring-formation and central-enhancement of matter, and is observed as the western half of the system containing the brightest knots near the center.

The intruder (face-on, western component) contains the major part of the CO gas as observed toward $(0'', 0'')$ and the bluer-peak H I. The relatively narrow velocity dispersion, ~ 140 km s^{-1}, of the CO gas in this component may be due to the fact that the line of sight is nearly face-on. The H I gas, which is more spread out, may have been more strongly disturbed to yield a larger velocity dispersion. The tidal disturbance from the other (wing) component has enhanced star formation in this intruder, leading to a clumpy irregular morphology.

The wing galaxy (nearly edge-on, eastern component) contains the redder-peak H I gas and a smaller amount of CO. The larger velocity dispersion of the CO profile observed at $15''$E than at the center (the intruder) is consistent with the assumption that we observed this galaxy nearly edge-on. The simulation (Taniguchi and Noguchi 1990) shows that a galaxy which experienced a radial penetration by the other, is more strongly disturbed than the other. This may be the reason why the wing galaxy contains little molecular gas: Gas in such a disturbed galaxy cannot survive in the form of low-temperature molecular clouds, but is dissociated and exists in the form of more extended, higher-temperature H I and/or H II gases. This may have yielded the observed small molecular-to-atomic hydrogen mass ratio in this wing component.

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