THE ASTROPHYSICAL JOURNAL, 321:L145–L149, 1987 October 15

GIANT MOLECULAR CLOUDS IN M31

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Received 1987 July 6; accepted 1987 July 23

ABSTRACT

We have mapped CO ($J = 1$–0) emission near the H II regions BA 292 and P248 in M31 with the Owens Valley interferometer at 7″ (25 pc) resolution. We resolve a cloud with characteristics similar to galactic giant molecular clouds (GMCs) such as Orion, including brightness, line width, size, mass, and the presence of active massive star formation. These observations provide strong evidence for the existence of GMCs in an external galaxy and indicate that in at least one region in M31 the CO flux is dominated by emission from GMCs. We find that all CO observations of M31 are consistent with an interstellar medium in which most of the molecular gas resides in GMCs.

Subject headings: galaxies: individual (M31) — galaxies: interstellar matter — interferometry — interstellar: molecules

I. INTRODUCTION

Because of its proximity (690 kpc), Andromeda is one of the few galaxies in which molecular clouds can be isolated by millimeter-wave telescopes. Using filled-aperture telescopes with diameters of 20–45 m, Boulanger *et al.* (1984), Ichikawa *et al.* (1985), Casoli, Combes, and Stark (1987), and Lada *et al.* (1987) have identified emission regions with masses similar to the giant molecular clouds (GMCs) in our Galaxy. However, the brightness temperature observed in these studies is always less than 0.6–0.8 K, an order of magnitude less than the brightness of galactic GMCs. These authors argue that the emission comes from GMCs since all other properties are similar to galactic GMCs, and attribute the low brightness to dilution in the 15″–30″ (50–100 pc) beams. Other interpretations are possible (e.g., Blitz 1985), and higher resolution observations are clearly required to confirm the nature of these clouds.

In the Milky Way Galaxy, GMCs dominate the molecular interstellar medium—most of the mass (Casoli, Combes, and Gerin 1984; Scoville and Sanders 1986; Dame *et al.* 1986) and most star formation (Scoville and Solomon 1974; Fich, Treffers, and Blitz 1982) are in GMCs. Although M31 resembles the Milky Way in some respects, there are important differences (e.g., Hodge 1982); in particular, the CO luminosity and the fraction of the interstellar medium in molecular form are significantly lower in M31. Although the CO surface brightnesses at $R = 10$ kpc are similar, the brightness in the Galaxy's molecular ring is a factor of 5 higher than emission anywhere in M31 (Stark 1985; Sanders, Scoville, and Solomon 1985). The question is whether, in spite of these differences, the molecular interstellar medium in M31 is also organized into GMCs. Higher angular resolution is clearly essential to determine if the basic physical properties of the M31 clouds, such as size, temperature, and line width, are similar to galactic GMCs, to investigate the association of the CO clouds with dust clouds, H II regions, and OB associations, and to measure the fraction of the molecular ISM contained in GMCs.

Lada *et al.* (1987) observed CO emission associated with the D118 dark cloud (Hodge 1981) in a spiral arm 7 kpc from the center of M31 using the Nobeyama 45 m telescope and identified three CO peaks with CO luminosities comparable to galactic GMCs. We mapped a field with 65″ half-power points centered on the SW peak; accounting for the inclination of M31, this corresponds to a 900 × 200 pc field of view. With ~ 7″ (25 pc) resolution, we clearly resolve the cloud and show that it has properties typical of GMCs in our Galaxy, which provides the strongest evidence yet for the existence of GMCs outside the Milky Way Galaxy.

II. OBSERVATIONS AND DATA REDUCTION

The CO ($J = 1$–0) observations were made during 1986 May–June and October with the Owens Valley Radio Observatory (OVRO) radio interferometer. Five configurations of the three 10.4 m telescopes, with baselines from 15 m to 55 m, were used to produce a synthesized beam of 8″.0 × 6″.6 at PA = 2°. The primary beam size was approximately 65″. The phases were calibrated by observing 0133+476 every half hour; we estimate that positions are uncertain to ~ 2″. The

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standard chopper wheel technique was used to correct for atmospheric attenuation and receiver gain variations. The flux density scale was determined by observations of W3(OH) (4.0 Jy) and Uranus ($T_B = 134$ K, Ulich 1981); the absolute fluxes have an uncertainty of 20%. The spectrometer was a filter-bank with 32 1 MHz channels, giving a coverage of 83 km s^{-1} at a resolution of 2.6 km s^{-1}. Maps were made using the NRAO AIPS software. The rms noise in a 1 MHz channel is 0.2 Jy. Detailed descriptions of the instrument are provided by Masson *et al.* (1985).

III. GIANT MOLECULAR CLOUDS IN M31

a) *Maps of* CO *Emission*

Maps of CO emission in 12 channels covering the velocity range of emission seen in single-dish observations are presented in Figure 1. CO emission is clearly detected in several channels centered at $V_{\rm LSR} \approx -530$ km s^{-1}; the brightness temperature peaks at 2.9 K (1.5 Jy beam^{-1}). No velocity gradient is evident. We average CO emission over the four channels with the strongest emission ($-535.6 < V_{\rm LSR} < -525.2$ km s^{-1}) to obtain the map shown in Figure 2 (*left*), which shows a CO cloud with a deconvolved Gaussian FWHM size of 70 × 20 pc. The properties of the cloud are summarized in Table 1. Observations of M31 are often corrected for projection along the minor axis; however, an inclination correction is not appropriate for structures which are smaller than the vertical scale height of the disk and which are not known to be elongated in the plane of the galaxy.

A spectrum of CO emission averaged over a 34″ × 16″ box centered on the CO cloud is shown in Figure 3. It is compared with a single dish spectrum obtained by J. Young at the FCRAO with a 50″ beam pointed toward the field center of the interferometer observations. There is a component at redshifted velocities which is resolved out by the interferometer; this component is discussed in detail in § III*d*. However, the cloud in Figure 2 (*left*) contains most of the flux at -532 km s^{-1} (80%) and -529 km s^{-1} (50%), which means that the source structure is almost certainly properly mapped.

b) *Active Massive Star Formation*

A contour map of integrated CO emission is overlaid in Figure 4 (Plate L12) on an Hα image obtained with the 4-Shooter CCD on the Palomar 5 m by Kulkarni and Shaya. The contours near the center of the figure show emission averaged over the same velocity range as in Figure 2. The contours at the east edge show emission averaged over $-525.2 < V_{\rm LSR} < -514.8$ km s^{-1}, the approximate velocity range of the middle CO peak observed by Lada *et al.* (1987); although the peak is only 3 σ, it coincides with the single-dish position within the errors. Corrected for primary beam attenuation since it lies 40″ from the pointing center, its flux is consistent with the single-dish flux.

The H II region ~ 5″ to the west of the main CO peak is BA292 (Baade and Arp 1964); several smaller H II regions also appear near the CO peak. The H II region near the second CO peak is Pellet 248 (Pellet *et al.* 1978). We will call the peaks BA 292(CO) and P248(CO), respectively. Although radial velocities of the H II regions are required for a definite association, the projected positions are sufficiently close that the CO clouds and H II regions are probably physically associated. Hence we conclude that BA 292(CO) and P248(CO) are sites of active massive star formation.

c) *Comparison with Galactic Giant Molecular Clouds*

A comparison with CO emission from Orion, the prototypical giant molecular cloud complex (e.g., Kutner *et al.* 1977), is useful for determining whether the M31 cloud is a GMC. We degraded the CO observations of Orion obtained by Maddalena *et al.* (1986) to the 27 × 22 pc resolution of the M31 observations by convolving with a 3°2 × 2°6 beam. The convolved Orion map of integrated CO flux is compared with the M31 map in Figure 2; at this resolution Orion A and Orion B are resolved but not clearly separated.

The properties of the two clouds are summarized in Table 2, which shows them to be remarkably similar. Both the M31 and Orion clouds consist of two principal peaks. The brightness temperature has a maximum of about 3 K in both Orion and M31, and the linewidth, size, and CO luminosity are the same to within 30%. Both are associated with H II regions. The molecular mass inferred from the CO flux is a factor of 2 greater than the virial mass in each region. The virial mass is probably underestimated because we used the FWHM diameters; if the area of detected CO emission were used instead, as in Maddalena *et al.*, the virial estimate would increase by a factor of 2. It may also be that the H_2/W(CO) ratio is lower than adopted.

All the observed properties, including brightness temperature, size, line width, and CO luminosity, lie in the range observed for galactic GMCs (e.g., Dame *et al.* 1986; Scoville and Sanders 1987). Another similarity with galactic GMCs is the coincidence with H II regions and active massive star formation; Waller *et al.* (1987) find that galactic radio H II regions are typically associated with GMCs of size 20–60 pc and mass 10^5–10^6 $M_\odot$.

Previous investigators (e.g., Stark 1979; Boulanger *et al.* 1984; Ichikawa *et al.* 1985; Casoli, Combes, and Stark 1987; Lada *et al.* 1987) have inferred the existence of GMCs in M31, based on the total luminosities, line widths, and (2–1)/(1–0) CO line ratios. Our observations, which reveal high brightness temperatures and close association with H II regions, show that in *every* important respect the M31 clouds are similar to galactic GMCs.

d) *The Fraction of Molecular Gas in Giant Molecular Clouds*

Since our observations clearly show that GMCs exist in M31, the remaining question is whether, as in the Galaxy, they contain most of the molecular gas. Together, the GMCs BA 292(CO) and P248(CO) account for 40% of the 150 Jy km s^{-1} detected in the 50″ FCRAO beam. At $V_{\rm LSR} < -528$ km s^{-1}, Figure 3 shows that most of the CO flux comes from BA 292(CO), which means at these velocities most of the molecular mass is in a GMC.

However, almost none of the flux at $V_{\rm LSR} > -525$ km s^{-1} is detected by the interferometer. P248(CO), located beyond the half-power point of the FCRAO beam, contributes about 15 Jy km s^{-1}. No additional sources are detected with the

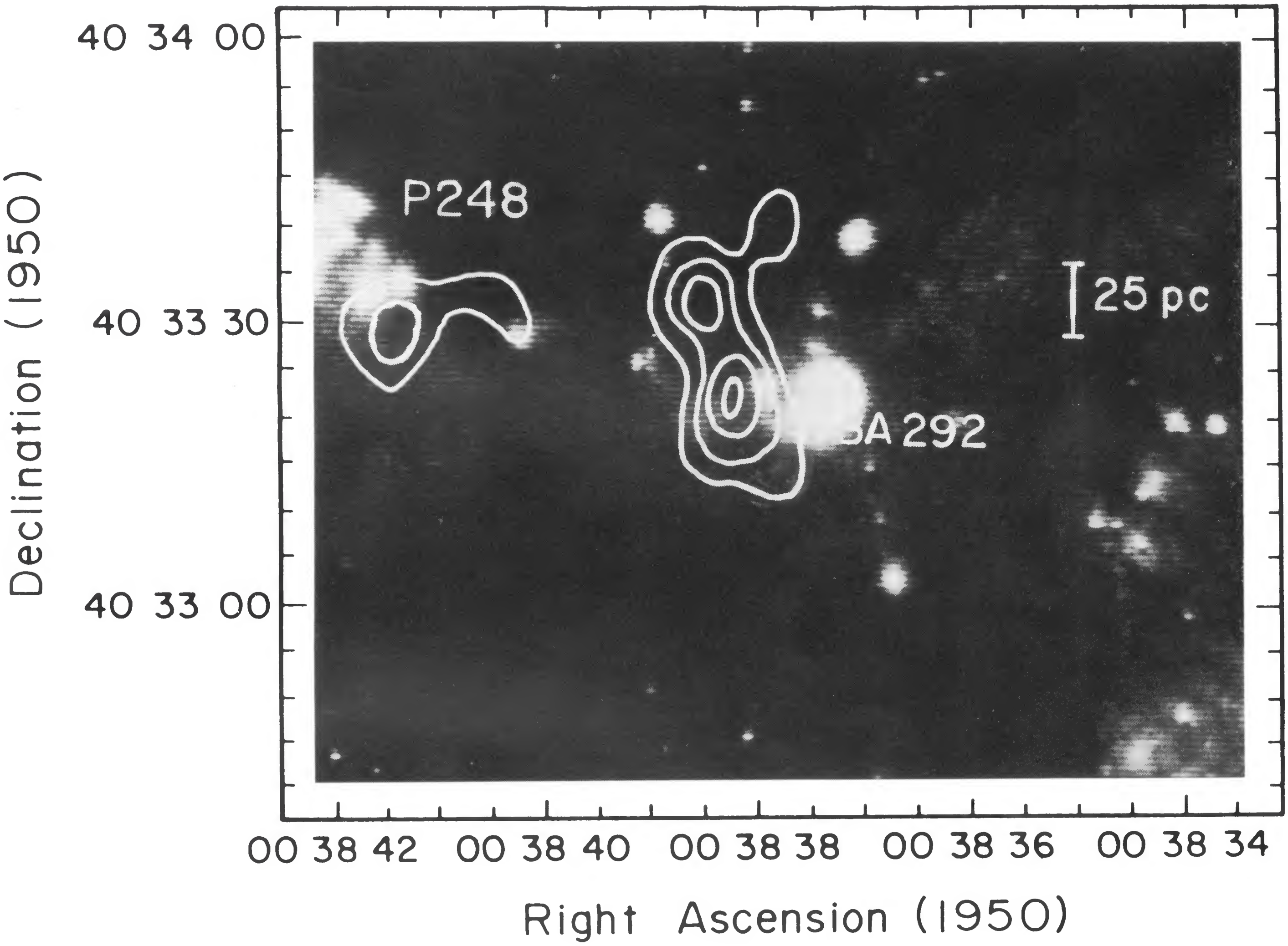

FIG. 4.—Contours of CO emission superposed on an Hα 4-Shooter CCD image obtained with the Palomar 5 m telescope by Kulkarni and Shaya. BA 292 is the bright emission region adjacent to the main CO emission peak. CO emission is averaged over the velocity range $-535.5 < V_{\rm LSR} < -525.2$ km s^{-1}, which produces the peak near the center, and $-525.2 < V_{\rm LSR} < -514.8$ km s^{-1}, which produces the eastern peak. Contours are at 2.6 Jy km s^{-1} intervals; for clarity only positive contours near the peaks are shown.

VOGEL, BOULANGER, AND BALL (*see* **321**, L146)

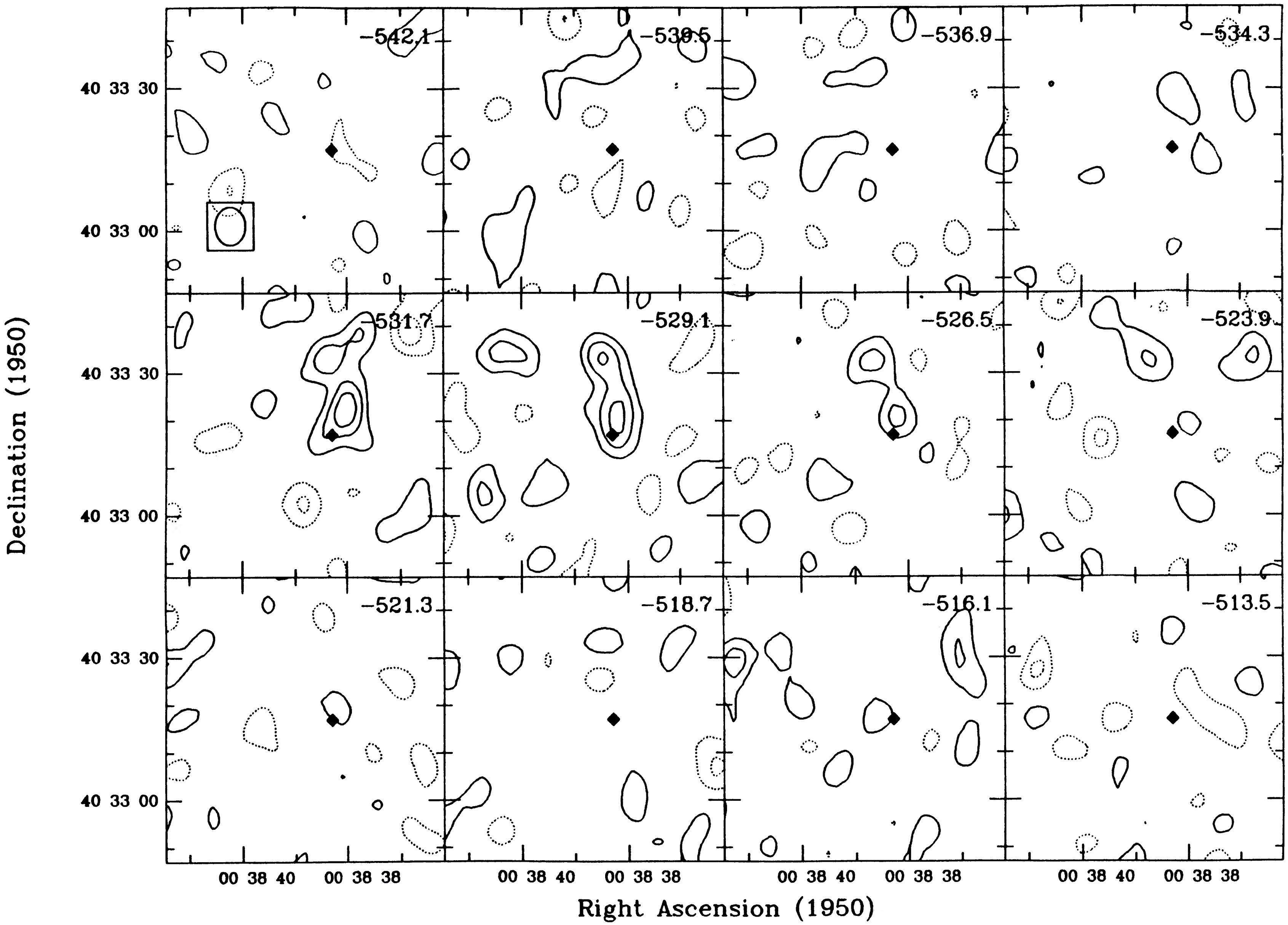

FIG. 1.—CO ($J = 1-0$) emission near M31 BA 292(CO). V_{LSR} is indicated in the upper right of each map. The contours are spaced at 0.4 Jy (0.7 K) intervals. The phase and pointing center is indicated by the diamond. The half power size of the synthesized beam is shown in the lower left of the first map.

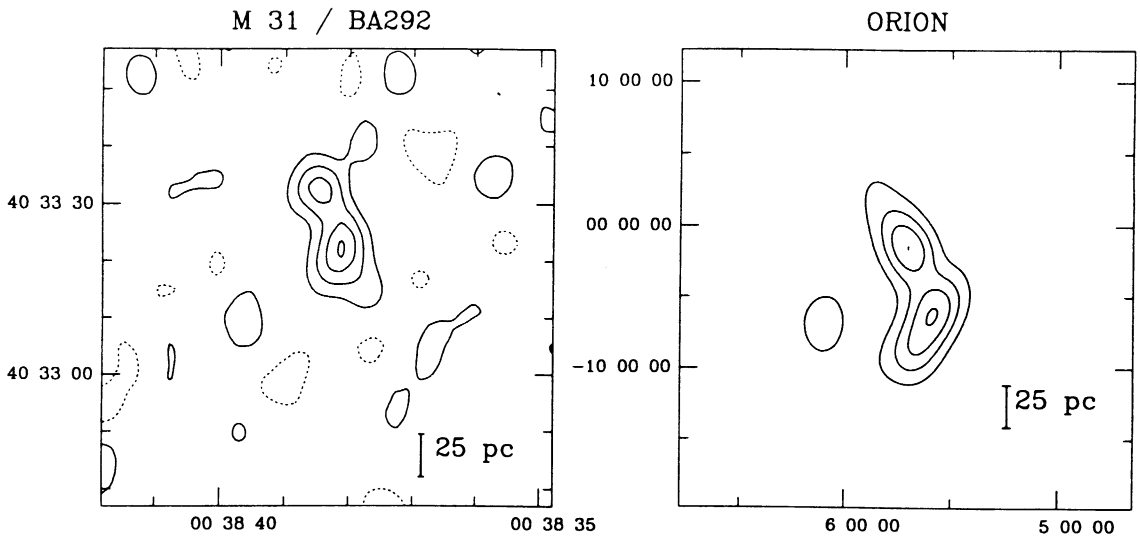

FIG. 2.—Comparison of integrated CO emission from the M31 BA 292(CO) (*left panel*) and the Orion (*right panel*) giant molecular clouds, both at 27 × 22 pc resolution. The Orion map was obtained by convolving the Maddalena *et al.* (1986) data to the 27 × 22 pc resolution of the M31 observations. The M31 and Orion maps are contoured at 2.6 and 1.4 Jy km s^{-1}, respectively; the Orion flux is scaled to the distance of M31.

TABLE 1

OBSERVED PARAMETERS OF BA 292(CO)

Parameter	Value
Size	22″ × 7″ ± 2; PA = 14°
Position (1950) ...	$00^h38^m37^s.95$; 40°33′25″.5 ± 2″
V_{LSR}	−530.1 ± 0.7 km s^{-1}
V_{FWHM}	7.0 ± 1.6 km s^{-1}
T_B (peak)	2.9 K ± 0.4 K
Integrated flux	42 Jy km s^{-1}

interferometer above a 4 σ level of 2 Jy km s^{-1} in the channel (2.6 km s^{-1}) maps and 5 Jy km s^{-1} in maps averaged over eight channels (20.8 km s^{-1}).

It is conceivable that the missing flux is in a large number of small clouds, the ensemble of which would certainly be resolved out by the interferometer. However, the surface density of these clouds would have to be a factor of 20 higher than the local high-latitude clouds observed by Blitz, Magnani, and Mundy (1984), using the assumptions in Blitz (1985).

The alternative is that, like emission at −530 km s^{-1}, emission at more redshifted velocities also originates from GMCs. If the remaining mass were in just one cloud, it would be easily detected. But if it were divided among several clouds, simulations using the *uv* coverage obtained for M31 show that the interferometer would, for many plausible source

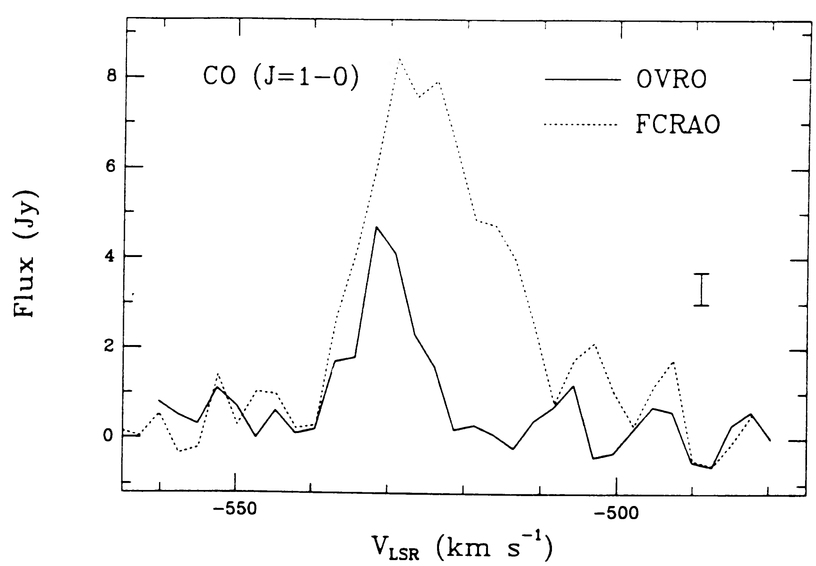

FIG. 3.—Interferometer spectrum (*solid line*) of CO 1–0 emission averaged over a 34 × 16″ box centered on the GMC BA 292(CO), compared with a single dish spectrum (*dotted line*) obtained by J. Young with the FCRAO telescope in a 50″ beam centered on the same region. The error bar indicates ±1 σ for the interferometer data.

TABLE 2

COMPARISON OF M31 BA 292(CO) AND ORION

Parameter	M31 BA 292(CO)	Orion A+B
Size (pc)	70×20	90×20
Peak brightness temperature (K)	3	3[a]
$V_{\rm FWHM}$ (km s^{-1})	7	5
CO luminosity (K km s^{-1} pc^2)......	49000	37000
Molecular mass ($M_\odot$)[b]	3.6×10^5	2.7×10^5
Virial mass ($M_\odot$)[c]	1.9×10^5	1.1×10^5

[a]Convolved to 27×22 pc resolution.

[b]Assumes the mean atomic weight per H atom is 1.36 and $N(H_2) = 3.6 \times 10^{20}$ $W_{\rm CO}$ cm^{-2} (K km $s^{-1})^{-1}$ (e.g., Scoville and Sanders 1987). The $N(H_2)/W_{\rm CO}$ ratio is uncertain; other evidence suggests that the ratio may be 30% lower (Bloemen *et al.* 1986).

[c]We use the virial theorem for a uniform spherical cloud. $M = 104\, V^2_{\rm FHWM}\, D({\rm pc})\, M_\odot$, and use the geometric mean of the major and minor axes for D.

distributions, fail to detect the clouds, due to a combination of resolution effects and lower brightness. Averaged over an area of more than 1 kpc^2, the properties of the M31 region are similar to the solar neighborhood. It is useful, therefore, to consider the cloud spectrum in the solar neighborhood. Within 1 kpc of the sun, 90% of the 5.7×10^6 $M_\odot$ of molecular gas is in 11 GMCs with $10^5 < M < 10^6$ $M_\odot$ (Dame *et al.* 1987, using our adopted conversion ratio). Since in the smaller 0.9×0.2 kpc^2 M31 region the mass is 1.3×10^6 $M_\odot$, it is reasonable to expect 3 or 4 GMCs. The velocity dispersion of GMCs in the solar neighborhood is 8 km s^{-1} (Stark 1984; Dame *et al.* 1987), exactly the value required to produce the linewidth observed in M31. The simplest interpretation consistent with the data is that emission at other velocities *also* originates primarily in several GMCs, and that the M31 region resembles the solar neighborhood.

All available observations of M31 (Boulanger *et al.* 1984; Blitz 1985; Ichikawa *et al.* 1985) can be explained by CO emission which comes mainly from GMCs, as argued by Stark (1979). For example, the average flux in the 20 regions detected by Blitz (1985) at 1′ resolution is nearly identical to the flux in the field mapped at OVRO; therefore, as with the BA 292(CO) field, GMCs with a distribution similar to the Galaxy can account for the flux, but small clouds must be an order of magnitude more abundant. The average dispersion of CO emission in the M31 emission regions is 5 km s^{-1}, 30% smaller than in the OVRO field; the measured dispersions range from 2.6 to 9.5 km s^{-1}. Clearly, the broad lines observed by Blitz and others do not require a population of very small clouds, but can be explained if, like the BA 292(CO) region, there are typically one to three or four GMCs in each field in which CO emission has been detected. It is of course impossible to unequivocally eliminate small clouds as a source of part of the flux. However, since small clouds would have to be much more abundant than in the Galaxy, whereas galactic GMCs fit the M31 data perfectly, it is likely that the bulk of the molecular ISM in M31 is in GMCs.

It is a pleasure to acknowledge the contributions of the staff at the Owens Valley Radio Observatory. We thank S. Kulkarni and E. Shaya for providing the Hα CCD images, J. Young for the FCRAO CO spectrum of BA 292, T. Stark for the Bell Labs CO data on M31, and R. Maddalena for the Orion data. We are also grateful to C. Lada for communicating results ahead of publication, and to N. Scoville, C. Lada, and M. Kutner for useful discussions. S. Mitra provided the simulations of the effects of *uv* coverage. The SiS junctions used in the receivers were provided by R. Miller of AT&T Bell Labs. The Hale 5 m telescope is operated by Palomar Observatory, California Institute of Technology. LLNL is under contract W-7405-ENG-48 with the US Department of Energy. S. N. V. was supported by NSF grant 84-112473 and by the Dudley Observatory.

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