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^{12}CO $J = 1$–0 OBSERVATIONS OF INDIVIDUAL GIANT MOLECULAR CLOUDS IN M81

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ABSTRACT

We present ^{12}CO $J = 1$–0 observations from the Caltech Millimeter Array of a field in the nearby spiral galaxy M81. We detect emission from three features that are the size of large giant molecular clouds (GMCs) in the Milky Way and M31, but are larger than any known in M33 or the SMC. The M81 clouds have diameters $\sim$100 pc and molecular masses $\sim 3 \times 10^5\ M_\odot$. These are the first GMCs to be detected in such an early-type galaxy (Sab) or in a normal galaxy outside the Local Group. The clouds we have detected do not obey the size–line width relation obeyed by GMCs in our Galaxy and in M33, and some of them may be GMC complexes that contain several small GMCs. One of these does show signs of substructure and is shaped like a ring section with three separate peaks. At the center of this ring section lies a giant H II region, which may be associated with the molecular clouds.
Subject headings: galaxies: individual (M81) — galaxies: ISM — H II regions — ISM: molecules

1. INTRODUCTION

Giant molecular clouds (GMCs) play an important role in the evolution of a galaxy. They are the sites of star formation, and thereby influence the evolution of a galaxy's stellar populations. The stars created in them can in turn influence the interstellar medium (ISM) through stellar winds and supernovae. GMCs are the dominant form of the molecular ISM and often contain most of the molecular material in a galaxy. The global properties of GMCs in the Milky Way are well known (Sanders, Scoville, & Solomon 1985; Digel, Bally, & Thaddeus 1990; Sodroski 1991). They are the most massive objects in the Galaxy, with masses in the range of 10^4–$10^6\ M_\odot$ and diameters from a few tens of parsecs to $\sim$100 pc. Hundreds of GMCs have been identified and studied in the Galaxy, and a few of these are now beginning to be studied in detail via high-resolution observations (e.g., Carpenter, Snell, & Schloerb 1995).

The properties of GMCs in external galaxies are less well known. The Magellanic Clouds have been surveyed and individual GMCs resolved using the SEST telescope (e.g., Kutner et al. 1997; Rubio, Lequeux, & Boulanger 1993). For other Local Group galaxies, interferometers have been used (M31: Vogel, Boulanger, & Ball 1987, Wilson & Rudolph 1993; M33: Wilson & Scoville 1990; IC 10: Wilson & Reid 1991, Wilson 1995; NGC 6822: Wilson 1994; NGC 205: Young & Lo 1996). Interferometric observations of the nearby starburst galaxy M82 have also identified GMC-like objects (Brouillet & Schilke 1993; Shen & Lo 1995). With the exception of the clouds in M82, which are bright and massive and more similar to clouds in the Galactic center, the GMCs in these galaxies are quite similar to those in the Milky Way. However, the clouds in the SMC tend to be smaller than those in the Galaxy. In addition, M33 appears to lack clouds with masses greater than $4 \times 10^5\ M_\odot$, while in our Galaxy the clouds have masses up to a few times $10^6\ M_\odot$. Except for these small differences, the GMCs in the various galaxies of the Local Group are very similar, despite enormous variations in the properties of the galaxies themselves, which range from early-type spirals (M31, an Sb) to late-type spirals (M33, an Scd), and from dwarf irregulars (IC 10, NGC 6822) to dwarf ellipticals (NGC 205). These observations suggest that the requirement of self-gravitation is more important in determining the properties of GMCs than is their environment.

To add to the list of galaxies with observations of individual GMCs, we have obtained CO observations of the nearby Sab galaxy M81. These observations are the first of such an early-type galaxy, as well as the first to resolve GMCs in a normal galaxy outside the Local Group. M81 is also interesting for this purpose because it has a strong radial metallicity gradient (Zaritsky, Kennicut, & Huchra 1994); and thus observations of several fields will allow a comparison of GMCs at different metal abundances to determine the effects of varying metal abundance on their global properties. This paper reports on our first detections of GMCs in one field in M81; the results of a larger, more sensitive survey currently in progress will be presented in a future paper.

2. OBSERVATIONS AND DATA REDUCTION

The Owens Valley Millimeter Wave Interferometer was used to observe a field in M81 in the ^{12}CO $J = 1$–0 line between 1997 February 19 and May 30. The field center was $\alpha(1950) = 09^h51^m32\overset{s}{.}9$, $\delta(1950) = 69°14'21''$, a position previously detected in the same line by Brouillet et al. (1991) using the NRAO 12 m telescope. The correlator was configured to provide two bandpasses simultaneously, each with 64 channels of 0.5 MHz (1.3 km s^{-1}) width. One bandpass was centered on the peak velocity of the single-dish detection, while the other was set adjacent to it to give a combined bandpass of $\sim$140 km s^{-1}. Approximately 8 hours were spent on source in each of the high- and low-resolution configurations. Flux and gain calibration were obtained by observing the nearby quasar 0923+392. This quasar was determined to have an average flux of 5.6 Jy from 12 observations in the 3 mm band over the period 1996 October 1 to 1997 June 17, for which observations of Neptune and Uranus were also available. The planets were not available during our observations themselves; calibration of the flux of 0923+392 relative to 3C 273 from our data agreed with the fluxes from the Owens Valley Radio Observatory (OVRO) calibrator database to within 10%. To be conservative, we adopt an absolute uncertainty of 20% in our absolute flux calibration.

All mapping was performed using the MIRIAD package. The data were averaged in velocity to obtain 1 MHz channel maps in the data cube. The noise in the 1 MHz channels of the dirty map was 0.052 Jy beam^{-1}. Cleaned maps were made of the bandpass containing the velocity of the single-dish detection. The synthesized beam is 3″.2 × 2″.7, with a position angle of $-24°$. This beam size corresponds to 56.3×47.5 pc at a distance of 3.63 Mpc (Freedman et al. 1994). The cleaned data cubes were searched for emission from GMCs using the procedures of Wilson & Scoville (1990). As a double check, each author conducted a search independently. Three clouds were identified that were common to both lists; in addition, there were four very weak features identified by one or the other of us that formally met the Wilson & Scoville (1990) criteria, but will not be discussed further until follow-up observations are obtained. As a further check on the reality of clouds, the bandpass offset from the velocity of the single-dish detection was mapped and searched for clouds. Two very weak features were found, similar to the ones found in the first bandpass, but nothing as strong as the three main cloud detections.

3. RESULTS

The observed and derived properties of the three clouds detected in our observations are given in Table 1. Given in the table are the position of each cloud, the peak velocity of the line in the frame of the local standard of rest, the full width at half-maximum velocity width, the peak brightness temperature of each cloud calculated from the maps with a conversion of 10.44 K Jy^{-1}, the integrated flux density, the deconvolved cloud diameters along the directions of right ascension and declination, the estimated virial mass, and the estimated molecular gas mass. The molecular mass was calculated using $M_{\rm mol} = 1.61 \times 10^4 d_{\rm Mpc}^2 S_{\rm CO}\ M_\odot$, where $d_{\rm Mpc}$ is the distance in megaparsec, $S_{\rm CO}$ is the flux density of the cloud in Jy km s^{-1}, and a factor of 1.36 is included to account for the mass of helium in the cloud. A Galactic value of the CO-to-H_2 conversion factor was also assumed [$\alpha = (3 \pm 1) \times 10^{20}$ cm^{-2} / (K km s^{-1}), Strong et al. 1988; Scoville & Sanders 1987]. This value is within 15% of the value suggested by the metallicity–conversion factor relationship of Wilson (1995) for the oxygen abundance of this region in M81 (Garnett & Shields 1987). Figure 1 shows the channel maps containing emission from the three clouds, while Figure 2 displays the area-integrated spectra for each of the clouds. Figure 3 shows the integrated CO emission for each cloud overlaid on an optical continuum-

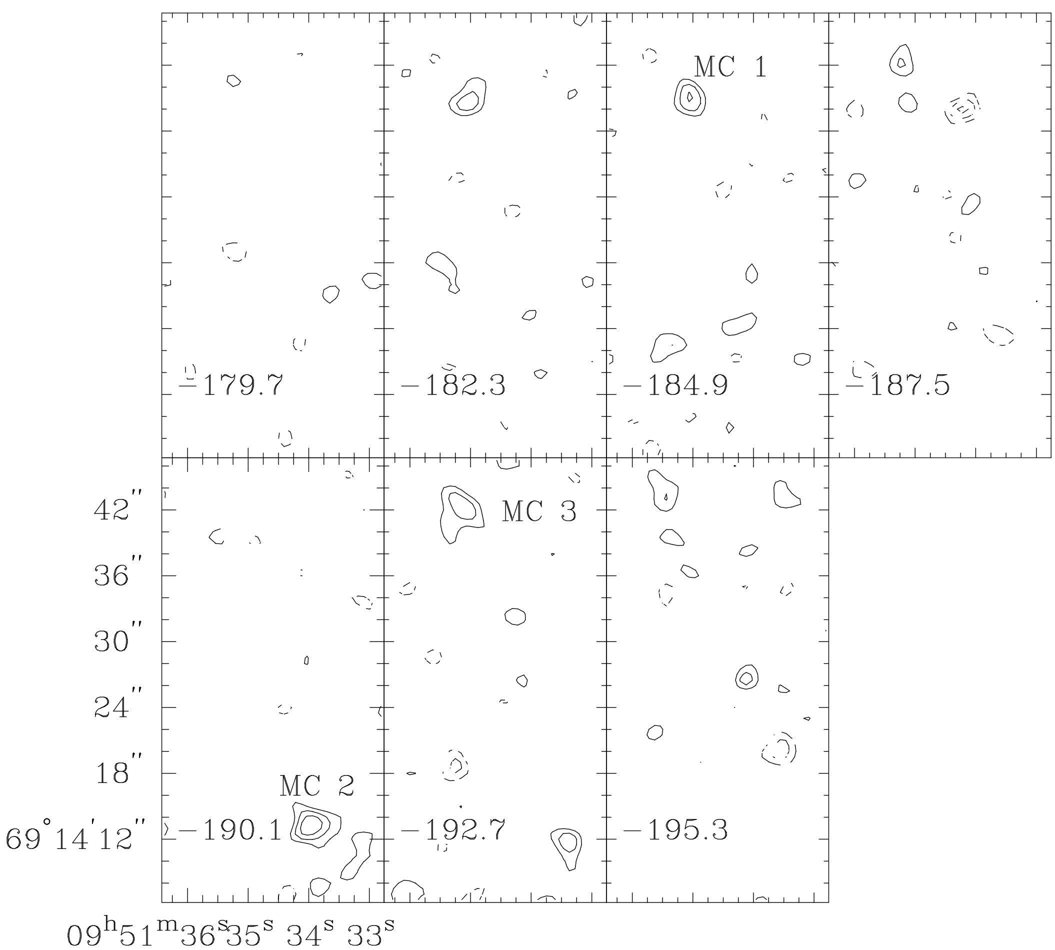

FIG. 1.—Channel maps showing the CO emission from the three M81 GMCs. The channels are 1 MHz (2.6 km s^{-1}) wide, and the contours are (-4, -3, -2, 2, 3, 4) × 0.052 Jy beam^{-1} = 1 σ. Negative contours are indicated by dashed lines, and the central velocity of each channel is given in the lower left corner.

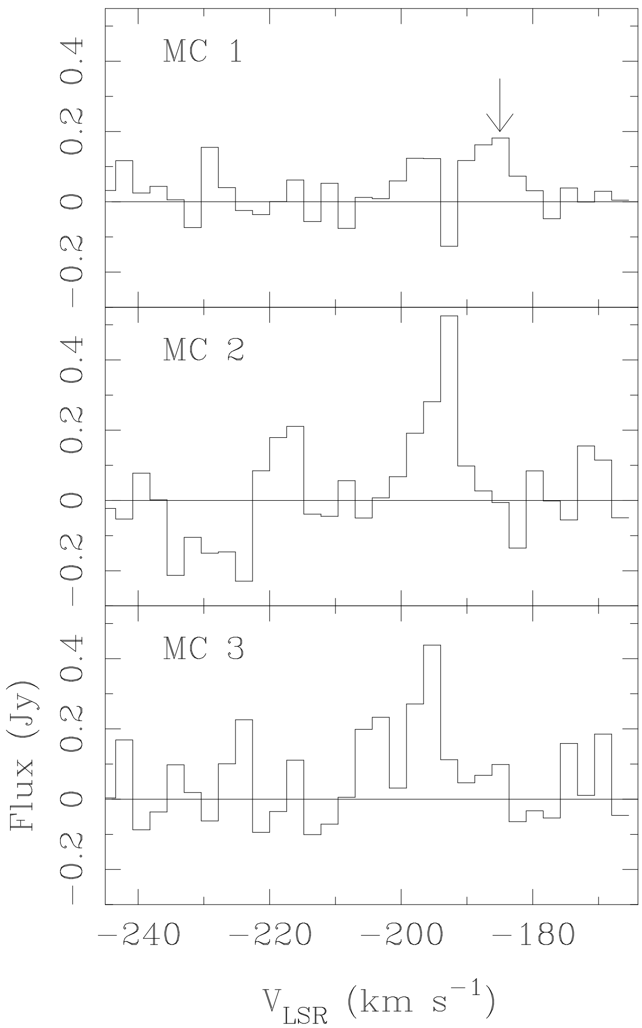

FIG. 2.—Spectra of the M81 GMCs obtained by integrating over the area of the CO emission through the channels of the data cube. The velocity of MC 1 is offset by $\sim$7 km s^{-1} from the other clouds and is indicated by the arrow.

subtracted [O III] image, and a similar image of the entire field, to show the relative positions of the clouds. Note that the figures have not been corrected for the falloff in sensitivity at the edges of the primary beam, but the flux measurements in Table 1 have been corrected by the appropriate factor. Below we discuss each of the clouds individually.

MC 1 (Fig. 3*a*) is unresolved by the synthesized beam. This cloud lies just to the southwest of a bright point source, which is likely a foreground star. There is no obvious counterpart in the optical image.

MC 2 (Fig. 3*b*) has the shape of a ring section and contains three separate peaks, each with roughly the same peak intensity. It is unresolved along the width of the ring. This cloud may in fact be a group of three clouds, similar to the Orion complex. The small line width ($V_{FWHM} = 4.7$ km s^{-1}) suggests that these three objects are related, while the small virial mass compared to the molecular mass (Table 1) suggests that the entire complex is gravitationally bound. In the optical image there is an H II region with [O III] line emission at the location of the CO emission. This H II region was also identified by Kaufman et al. (1987, their No. 172), who measured a 20 cm continuum flux density of 0.57 ± 0.11 mJy, a 6 cm flux density of 0.52 ± 0.07 mJy, and a spectral index of -0.08 ± 0.19. The flat spectral index (consistent with zero) indicates that the radio continuum flux is entirely thermal in origin, and that there are no supernova remnants associated with the H II region. This could be an indication that the H II region is relatively young. This H II region was also one of those used by Garnett & Shields (1987, their No. 2) in their study of the distribution of metal abundance in M81. From their spectra they estimated the number of ionizing photons per second to be 6.4×10^{50}, the oxygen abundance to be $12 + \log$ (O/H) = 8.79, and the electron temperature, T_e, to be 7200 K.

MC 3 (Fig. 3*c*) is irregularly shaped and elongated along a position angle of $\sim 45°$. Unlike MC 2, it does not appear to have any substructure, and is resolved in all directions. It is located just north of MC 1, but is separated in velocity by 8 km s^{-1}. Because of the proximity of MC 3 to MC 1, it is reasonable to consider whether they are in fact two components of a single cloud. However, the boundaries of the two clouds are distinct at the 50% of peak intensity contour, while the peaks of the two clouds are separated by 90 pc in *projected* distance, and the extreme edges by nearly twice that. These properties, together with the combined emission spectrum that shows a dip to zero emission between the peak intensities of the two clouds, strongly suggest that these are two separate clouds.

4. DISCUSSION

The field we have observed was observed by Brouillet et al. (1991) with the NRAO 12 m telescope as their field S6, for which they reported an integrated intensity, I_{CO}, of 0.4 K km s^{-1}. Assuming a gain of 34 Jy K^{-1}, this intensity corresponds to an integrated flux density of 13.6 Jy km s^{-1}, while we have detected a total of 7.9 Jy km s^{-1} in these three clouds. Clearly we have not detected all the flux observed by Brouillet et al. (1991). There are two possible explanations

TABLE 1

PROPERTIES OF GMCs IN M81

Cloud	α(1950)	δ(1950)	V_{peak} (km s^{-1})	V_{FWHM} (km s^{-1})	T_B (K)	S_{CO} (Jy km s^{-1})	$D_\alpha \times D_\delta$[a] (pc)	M_{vir}[b] ($10^5\ M_\odot$)	M_{mol}[c] ($10^5\ M_\odot$)
MC 1......	09 51 35.1	69 14 39	−184.9	7.7	3.0	1.6	...	...	3.4
MC 2......	09 51 33.6	69 14 11	−190.1	4.7	2.9	3.1	93 × 100	3.0	6.5
MC 3......	09 51 35.4	69 14 43	−192.7	4.9	3.2	3.2	121 × 72	3.2	6.9

NOTES.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Distance to M81 of 3.63 Mpc is assumed. Typical errors are $D_{\alpha,\delta}$, ± 10 pc; V_{FWHM}, ±1.3 km s^{-1}; S_{CO}, ± 20%; M_{mol}, ± 30%; M_{vir}, ± 40%.

[a] D_α and D_δ are the deconvolved FWHM diameters in the right ascension and declination directions.

[b] Assumes a $1/r$ density distribution and a spherical cloud, $M = 99\ V^2_{FWHM} \bar{D}\ M_\odot$, where $\bar{D} = 1.4(D_\alpha + D_\delta)/2$ (Wilson & Scoville 1990).

[c] Assumes $\alpha = 3 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$.

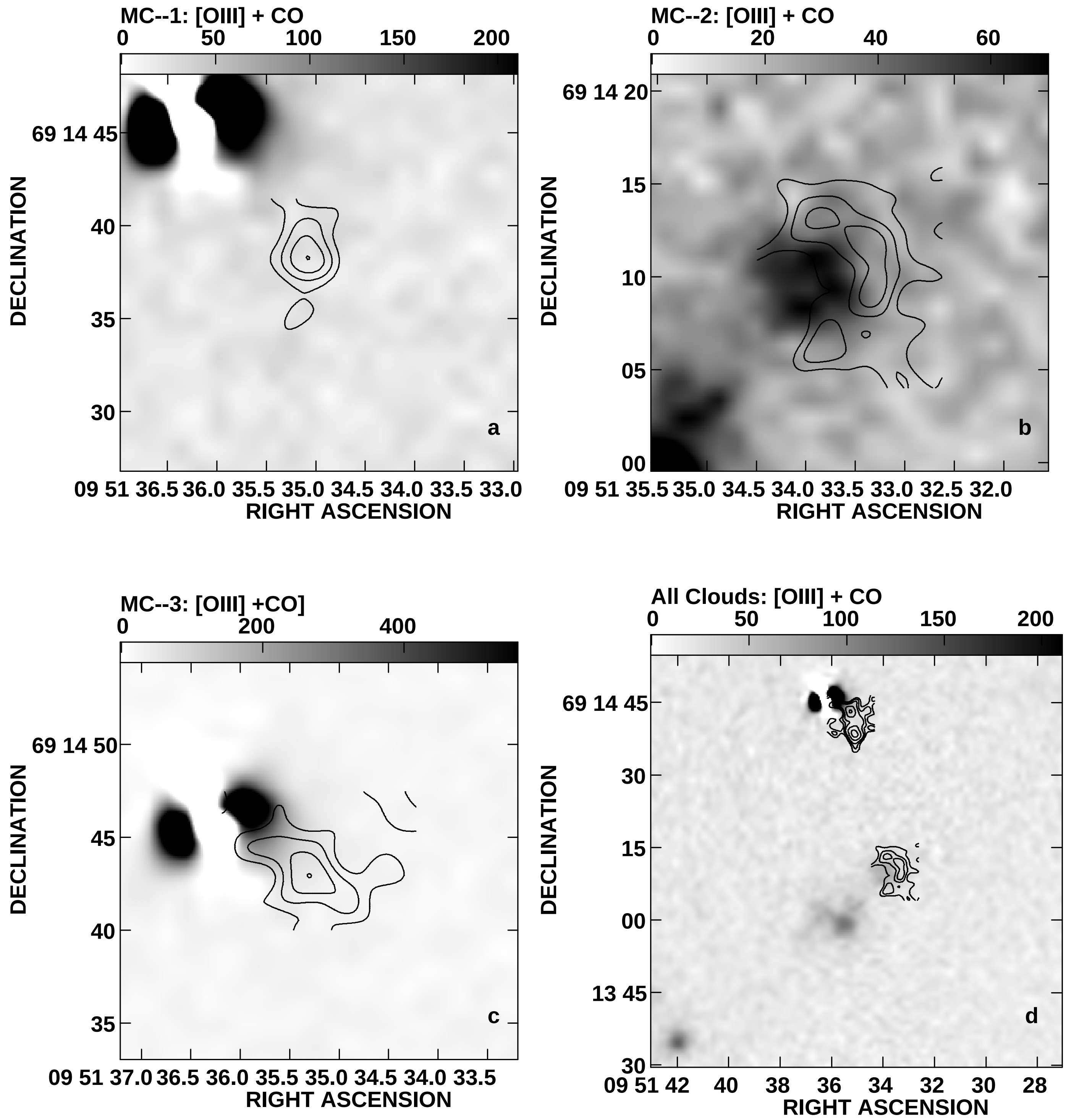

FIG. 3.—Overlays of [O III] – CO. Optical images in the line and neighboring continuum were obtained from the NCSA Astronomy Digital Image Library. Images were registered, the continuum was subtracted, and the resulting image was registered with our CO maps. (*a*) MC 1: CO contours are (1, 2, 3, 4) × 0.338 Jy beam^{-1} km s^{-1} = 1 σ, and the map was made by averaging over 5 MHz. (*b*) MC 2: CO contours are (1, 2, 3) × 0.2028 Jy beam^{-1} km s^{-1} = 1 σ, and the map was made by averaging over 2 MHz. (*c*) MC 3: CO contours are (1, 2, 3, 4) × 0.312 Jy beam^{-1} km s^{-1} = 1 σ, and the map was made by averaging over 4 MHz. (*d*) Entire field, showing the relative positions of the clouds. The CO contours are (1, 2, 3, 5, 7) × 0.2028 Jy beam^{-1} km s^{-1}. The southern spiral arm of M81 can be traced out along the line of H II regions running from northwest to southeast through the image.

for this: (1) our interferometric observations are missing flux due to missing short baselines in our *u*-*v* coverage, or (2) the missing flux is weak enough to be below our detection threshold, i.e., *in GMCs not massive enough to detect in our data.* These explanations are not mutually exclusive; for example, we could be missing an extended component of molecular gas with low column density. The width of the single-dish line is 14.2 km s^{-1}, while the spread in velocities of the different clouds that we have detected is 7.8 km s^{-1}, which suggests that we are missing a component of the molecular ISM with a larger velocity dispersion than the large clouds we have found. This result is similar to what is seen in M33, where the single-dish line widths are also larger than the velocity dispersion of the clouds seen interferometrically (Wilson & Scoville 1990). The missing component could be either lower mass molecular clouds or a population of translucent or high-latitude molecular clouds, such as are seen in the Milky Way (e.g. Blitz, Magnani, & Mundy 1984).

One important question is how the properties of the clouds in M81 compare to those in other galaxies. From Table 1 we see that the molecular mass of the clouds is on the order of $3 \times 10^5\ M_\odot$. Such masses would not be unusual for clouds in the Milky Way or M31 (Wilson & Rudolph 1993), but would be at the extreme high end of the distribution in M33 (Wilson & Scoville 1990) and are larger than the cloud masses in the SMC (Rubio et al. 1993). There is a similar trend for the physical sizes of the GMCs: the M81 clouds have diameters ~ 100 pc, similar to the largest GMCs known in the Milky Way (Sodroski 1991), but much larger than what is seen in M31 (although to date there are only four GMCs known in M31). In M33 the diameters only reach ~ 60 pc, and the SMC clouds are smaller still. It is possible that the maximum mass and diameter of GMCs depend upon the morphology of the host galaxy in such a way that late-type galaxies have smaller, less massive GMCs than early-type galaxies. To prove this conjecture will require more extensive searches for GMCs in galaxies like M31 and M81, as well as extending the searches to more galaxies to achieve sufficient numbers of galaxies for statistical analyses.

A third property to compare is the line width, which is thought to be a measure of the clump-clump velocity dispersion within GMCs. For the three M81 clouds, the line width lies between 4.7 and 7.7 km s^{-1}, which is well within the range spanned by the GMCs in M33, M31, IC 10, and the SMC. However, given the large sizes of these clouds, the line widths are somewhat low. Figure 4 plots the size–line-width relation for the two resolved clouds from M81 and 18 GMCs from M31, M33, and IC 10. The curve drawn in the figure shows the size–line-width relation fitted by Wilson & Scoville (1990) to the GMCs in M33, $V_{\rm FWHM} = 1.2D_{\rm pc}^{0.5}$. Similar curves have been fitted to the population of GMCs in the Milky Way (e.g., Sanders et al. 1985; Sodroski 1991). The existence of this relationship has by some authors (e.g., Issa, MacLaren, & Wolfendale 1990) been attributed to the criteria used to define the borders of a cloud and the crowded condition of the GMCs, both spatially and in velocity in the inner Galaxy. This argument is not applicable to GMCs in the outer Galaxy, or in other galaxies, where the same sort of relationship has been found (Sodroski 1991; Wilson & Scoville 1990).

The clouds in M81 do not obey this size–line-width relationship, with line widths that are too small for their sizes. Similarly narrow line widths are found by Brouillet et al. (1997) for six molecular complexes in a different region of M81. Although the clouds we have discovered appear to be gravitationally bound (Table 1), they may not be individual GMCs. This possibility is especially true of MC 2, which has the shape of a circular arc, and shows three distinct peaks in the spatial distribution of its CO emission. In this case, perhaps the three peaks represent GMCs that would obey the size–line-width relationship if they could be observed with high enough spatial resolution. An analog to this in our own Galaxy may be the Orion molecular complex. The diameter of this complex is approximately 130 pc, and the molecular mass inferred from the CO emission is $2.3 \times 10^5\ M_\odot$ (Maddalena et al. 1986). The composite line width for all the clouds in the complex, including the neighboring Monoceros R2 complex, is 6 km s^{-1} (Maddalena et al. 1986), similar to that of our MC 2.

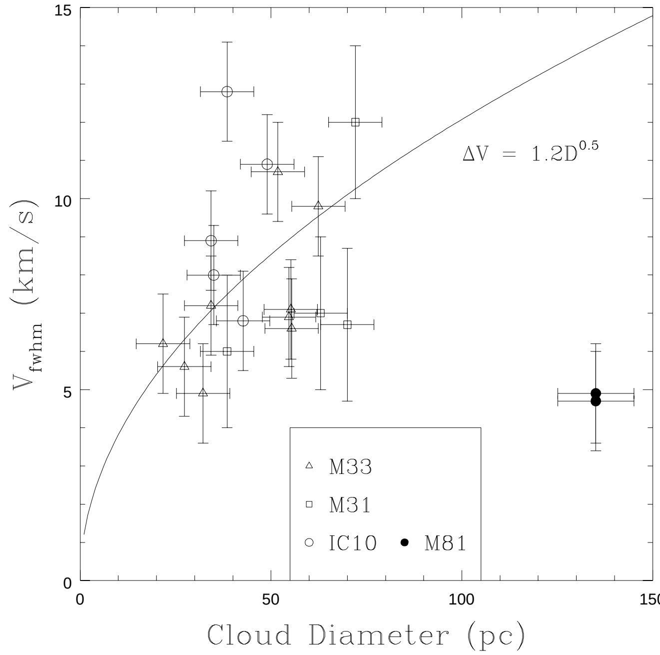

FIG. 4.—Plot of line width vs. diameter for GMCs in M33 (*triangles*), M31 (*squares*), IC 10 (*open circles*), and M81 (*filled circles*). The curve shows the size–line-width relation fitted to GMCs in M33 by Wilson & Scoville (1990).

5. SUMMARY

We have reported on ^{12}CO $J = 1$–0 interferometric observations of a field in M81 with the Owens Valley Millimeter Array. With its high resolution, we have detected three emission features that are roughly the size and mass of the largest giant molecular clouds in the Galaxy. M81 is now the earliest type and most distant normal galaxy in which GMCs have been detected. One of these clouds is shaped like a circular arc, with a giant H II region at the center. The clouds we have detected, although similar to the largest GMCs in M31 and our own Galaxy, are more massive and larger than those seen in later-type galaxies such as M33 and the SMC. At least two of the three detected clouds do not obey the size–line-width relationship as delineated by GMCs in the Milky Way and M33. Thus, these objects may not be individual GMCs, but may instead be complexes of several clouds, like the Orion complex in our Galaxy. We plan to extend this work by observing with greater sensitivity to detect less massive clouds and by observing other fields in M81 to compare the properties of GMCs at different locations within the galaxy.

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