THE ASTROPHYSICAL JOURNAL, 461:202–209, 1996 April 10

MOLECULAR GAS IN THE IRREGULAR GALAXY NGC 4449

DEIDRE A. HUNTER
Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001

AND

HARLEY A. THRONSON, JR.
Wyoming Infrared Observatory, University of Wyoming, Laramie, WY 82071
Received 1995 May 1; accepted 1995 October 13

ABSTRACT

We present observations of the CO ($J = 1$–0) molecular emission in the actively star-forming irregular galaxy NGC 4449. Observations of eight positions within the optical galaxy cover a variety of H I cloud locations and levels of star-formation activity. Within a beam of 1.7 kpc we detect 1–4 × 10^7 $M_{\odot}$ of M_{H_2} in six positions, assuming conversion of CO emission to H_2 as appropriate for irregular galaxies and a large beam size. The size of the telescope beam, the high masses of molecular material, and the relatively high velocity dispersions observed suggest that these are molecular cloud complexes, similar to some of those found in other nearby, late-type galaxies. Except for the center of the galaxy, the molecular mass, molecular and peak H I column densities, and the ratio $M_{H_2}/M_{H\,I}$ do not vary by more than a factor of 2 between the positions. The low molecular-to-atomic gas mass ratio and high H I column densities are consistent with the molecular material being the cores of dense atomic clouds, where it is protected from UV radiation. Regions with few or no bright H II regions have molecular gas masses and gas column densities similar to those in regions containing many sites of star formation. It is not clear whether these regions will become active in the future.

Subject headings: galaxies: individual (NGC 4449) — galaxies: irregular — galaxies: ISM — ISM: molecules — radio lines: galaxies

1. INTRODUCTION

In the Milky Way it is seen that stars form out of the molecular (H_2) clouds. In more distant galaxies, therefore, it seems reasonable that one must assess the dense, molecular gas content in order to fully understand the relationship between the gas and the star formation. For this purpose, the CO molecule is the most readily observed tracer of the molecular gas. Because of their low CO luminosities (Elmegreen, Elmegreen, & Morris 1980; Israel et al. 1982; Verter 1987; Thronson & Bally 1987; Tacconi & Young 1985; Hunter & Sage 1993), molecular observations of irregular galaxies have been particularly difficult to obtain and few irregulars have been mapped.

Yet irregular galaxies serve as an important laboratory in which to examine the star formation process. These smaller systems have lower rotation velocities and often near rigid-body rotation curves, and therefore lack the levels of shear and density shock waves that characterize spiral disks. Furthermore, many Im galaxies are actively forming stars, indicating that spiral density waves are not necessary to a vigorous production of massive stars (Hunter & Gallagher 1986). In addition, irregulars are less dusty, more gas rich, and lower in metallicity than spirals. All of these differences could, in principle, translate into differences in the star formation process (see Shields & Tinsley 1976; Wolfire & Cassinelli 1987; Larson 1981). Therefore, the Im galaxies, which are among the most common galaxy type in the universe, provide both a different and simpler environment in which to investigate processes of star formation.

Some molecular mapping of one actively star-forming Magellanic-type irregular, NGC 4449, has been undertaken. CO observations have been made of the center of NGC 4449, along the bar (Tacconi & Young 1985; Thronson et al. 1987; Sasaki, Ohta, & Saito 1990), where Hα images show that intense star formation has been taking place. However, one might expect regions of intense UV radiation to be harsh environments for molecular clouds. Furthermore, a Very Large Array (VLA) B-array map of 21 cm H I emission from NGC 4449 (Hunter, van Woerden, & Gallagher 1996, in preparation) revealed large H I complexes of gas located outside the central region. In the Milky Way and M101, giant molecular clouds are often associated with large H I clouds (Blitz & Shu 1980; Blitz et al. 1981). This has also been seen in some irregulars, such as the 30 Doradus region in the LMC (Cohen et al. 1988; McGee & Milton 1966) and in IC10 (Ohta et al. 1992). Hence, we might expect to find CO emission associated with the H I peaks in NGC 4449.

In particular, the VLA H I map of NGC 4449 had revealed three H I complexes located about 2′–3′ from the center of the galaxy. These complexes are large (1′ × 1′.4–2′.8 = 1.4 × 2.2–4.4 kpc; for a distance of 5.4 Mpc) and appear to contain a considerable amount of gas; yet the star formation activity in two of the complexes, as shown by Hα images and far-infrared maps, appears to be minimal. It is possible, therefore, that star formation is just getting underway in these two complexes; and, if this is indeed the case, they afford an opportunity to measure the CO content before the molecular clouds are modified by star formation. Alternatively, star formation may not be related to the presence or absence of H I.

Therefore, we undertook CO observations of NGC 4449 in order to explore the relationship between the molecular gas, the H I gas, and star formation. We used the National Radio Astronomy Observatory's (NRAO)[1] 12 m telescope. The beam of that telescope (65″) was ideally suited to the

[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

apparent sizes of the H I complexes as seen in the B-array H I map. We sampled a variety of environments: several positions in the H I cloud complexes that contain little obvious star formation, positions that currently contain numerous H II regions, and several areas outside of the H I complexes that were obvious in the VLA map. Six regions were reliably detected in CO. We report the results of these observations and their relationship to the atomic gas and star formation activity. For our assumed distance of 5.4 Mpc (based on $H_0 = 50$ km s^{-1} Mpc^{-1}), the beam of the telescope corresponds to 1.7 kpc at NGC 4449.

2. OBSERVATIONS AND REDUCTIONS

Observations of NGC 4449 in the ^{12}CO ($J = 1$–0) molecule were made in 1988 May and June with the 3.0 mm SIS receiver on the NRAO 12 m telescope. The filter bank had 128 channels, each 2.6 km s^{-1} in width for a total velocity coverage of 330 km s^{-1}. The telescope was beam-switched between source and a blank sky location about 10′ to the south of the galaxy. A calibration source was observed after every 6 minute scan.

There was a mechanical problem with the calibration hot load that introduced a scaling factor, but the error was constant. Periodic observations of standard sources—W3(OH), Orion A, IRC 10°216, DR 21(OH)—in combination with another program's observations (Hunter, Thronson, & Wilton 1990) were used to determine the scaling factor. Differences among sources yielded a 20% uncertainty in the calibration.

The scans were reduced at NRAO. We subtracted linear baselines, measured peak temperatures and velocities, and integrated over the spectral features. A Hanning smoothing was applied to the final spectra. The integration times, measurements, and derived parameters are given in Table 1.

To derive the column densities N_{H_2} and molecular hydrogen masses M_{H_2} requires adoption of a conversion factor, usually designated as $X = N_{H_2}/I_{CO}$. Evidence is mounting that this factor is a function of the metallicity of the gas as well as the linear resolution of the beam used to make the observations (Verter & Hodge 1995). Figure 2 of Verter & Hodge shows the range in derived X-values as a function of these two parameters, where the observations are divided up into those made with beams larger than 100 pc at the galaxy and those made with smaller beams. The X-factor is seen to be larger for larger beam sizes and for lower oxygen abundances. The oxygen abundance O/H of NGC 4449 has been measured by Hunter, Gallagher, & Rautenkranz (1982) to be 4.0×10^{-4}, and the beam size is large. From Figure 2 of Verter & Hodge that would imply an X-value of 16×10^{20} cm^{-2} (K km s^{-1})$^{-1}$, a value that is 5 times higher than the Galactic value of 3×10^{20} cm^{-2} (K km s^{-1})$^{-1}$ determined from gamma-ray observations (Bloemen et al. 1986). We note, however, that Talent (1980) has measured an oxygen abundance for NGC 4449 that is a factor of 2 lower. For this metallicity, the conversion factor X in Figure 2 of Verter & Hodge could be anywhere from the value quoted above to a value 4 times higher. We have chosen to adopt the value 16×10^{20} cm^{-2} (K km s^{-1})$^{-1}$, but recognize that there is at least a factor of 4 uncertainty. There is additional uncertainty due to the fact that the size of the beam at NGC 4449 is larger than most other observations of irregular galaxies, and the trend with beam size would indicate that the value of X could even be higher. The uncertainty in the value of X is by far the dominate source of uncertainty in the derived parameters. The molecular hydrogen mass, M_{H_2}, is estimated from $I(^{12}\text{CO})$ with a scaling factor of 33×10^6 $M_\odot$ (K km s^{-1})$^{-1}$, which includes the factor of 5 just discussed.

Given the uncertainty in the value of X, we have chosen not to correct the column densities for the inclination of the galaxy, which enters as cos i, where i is the galaxy's inclination angle. The inclination of NGC 4449 is uncertain, because the instrinsic shape of the galaxy may not be "standard." NGC 4449 is largely face-on, and if one does assume a standard instrinsic shape, the inclination would be 31°. This would mean a factor of 0.86 correction to column densities; ratios, however, would not be affected.

We have used the H I line maps of Hunter, van Woerden, & Gallagher (1996, in preparation) to outline the H I peaks in NGC 4449 and to measure the atomic gas mass in the regions observed with the 12 m beam. The Hunter et al. observations combine data from the B, C, and D arrays of the VLA, and the maps used here were made and cleaned with natural weighting and a beam of FWHM 6″.2 × 7″.4. The rms noise is 0.6 mJy beam^{-1}, and the channel separation was 5.16 km s^{-1}. An integrated H I map was made by summing all of the channels with detectable signal.

Figure 1 shows a single contour from the integrated H I map. The contour, 4×10^{21} cm^{-2}, is chosen in order to outline the H I complexes, and the relationship between H I column densities and H_2 will be discussed below. The H I contour is placed on a stacked Hα image obtained with the Perkins 1.8 m telescope at Lowell Observatory through a 30 Å FWHM filter. The detector was an 800 × 800 TI CCD obtained by Lowell Observatory from the National Science Foundation, and it was placed behind the Ohio State University's Fabry-Perot, which was used as a simple 5:1 focal reducer. The stellar continuum, imaged with a filter centered at 6438 Å and with a FWHM of 95 Å, has been subtracted to leave just the ionized gas. The numbered

TABLE 1

THE CO MEASUREMENTS

Region	Time (minutes)	$I(^{12}\text{CO})$ (K km s^{-1})	N_{H_2} (10^{21} cm^{-2})	M_{H_2} (10^7 $M_\odot$)	$M_{H_2}/M_{H_2(\text{cen})}$	V_r (km s^{-1})	ΔV (km s^{-1})
1	144	1.35 ± 0.10	2.2	4.4 ± 0.4	1.0	229	19
2	300	0.42 ± 0.08	0.7	1.4 ± 0.3	0.3	216	11
3	126	0.53 ± 0.13	0.9	1.7 ± 0.5	0.4	237	23
4	228	0.66 ± 0.06	1.1	2.2 ± 0.2	0.5	225	21
5	216	0.15 ± 0.08	≤0.2	≤0.5 ± 0.3	≤0.1	232:	16:
6	570	0.30 ± 0.05	0.5	1.0 ± 0.2	0.2	220	16
7	252	0.43 ± 0.08	0.7	1.4 ± 0.3	0.3	241	21
8	114	0.32 ± 0.11	≤0.5	≤1.0 ± 0.4	≤0.2	209:	11:

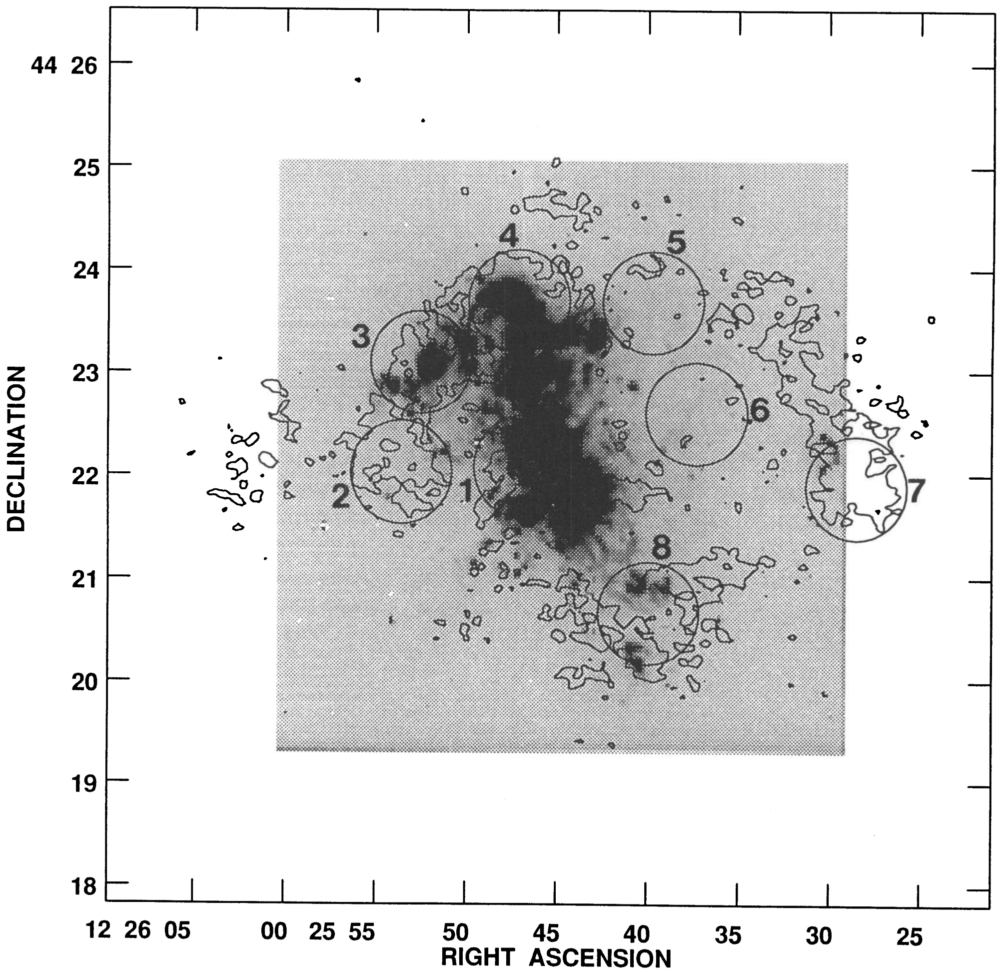

FIG. 1.—Integrated H I contours from Hunter et al. (1996, in preparation) are superposed on an Hα image of NGC 4449. One H I contour level, 4×10^{21} cm^{-2}, is shown in order to outline the H I complexes in the central region of the galaxy. The circles indicate the positions and size of the 12 m CO observations. The numbers identify the measurements given in Table 1.

circles in Figure 1 show the positions of the 12 m CO observations, and the size of the circle corresponds to the size of the 12 m beam. The CO spectra are shown in Figure 2.

The mass of H I, assuming that it is optically thin, and the Hα fluxes within the area of the 12 m telescope beam outlined in Figure 1 have been estimated from the integrated H I map and from the optical Hα emission image. These measurements are given in Table 2 along with comparisons with the H_2 masses. The ratios are for measurements over the same area of the galaxy. The CO central velocities given in Table 1 agree to within 6 km s^{-1} with the estimated peak H I velocities in the same region. Therefore, it is likely that the bulk of the H I that we measure in the same area on the sky as a CO observation is physically associated with that molecular material. The total H I mass in NGC 4449 is greater than 2×10^9 $M_\odot$ (Hunter & Gallagher 1985), and so the amount of atomic mass measured within the circles in Figure 1 represents a few percent of the galaxy's total supply.

3. RESULTS

3.1. *The Molecular Clouds*

Molecular CO emission was detected reliably in six of the eight positions shown in Figure 1. Position 1, the center of the galaxy, is the brightest of our observations and has been observed before. Positions 5 and 8 are very weak (1–2 σ) detections in CO, at best; therefore, we treat these measurements as upper limits. Position 5 is an inter-H I complex observation, and position 8 straddles two H I clouds. Thronson et al. (1987) observed a region near our position 1 with the same telescope. They measured an integrated line intensity that is 25% lower than what we obtained, a difference that is within the uncertainties of the two observations. Thronson et al. also detected a location that is between our regions 1 and 4 in the northern part of the galaxy and a pointing that lies between our regions 1 and 8 in the southwest part of the galaxy. With the conversion factor that we have used, their observations give masses of 2×10^7 $M_\odot$ for their northern position, close to that which we obtain for position 4, and 3×10^7 $M_\odot$ for the southern observation, a value that is midway between the measurements for the positions on either side. Thus, our measurements are consistent with those of Thronson et al.

NGC 4449 has also been observed in CO at much higher resolution by Sasaki et al. (1990). They used the telescope at Nobeyama (17″ beam) to map a cross pattern down the major axis of the optical galaxy. They detected CO in two cloud complexes near the center and southeast of the center of the galaxy. Our position 1 includes parts of their two cloud complexes. They obtained masses of 4–6 $\times 10^7$ $M_\odot$ for the molecular complexes, which is comparable to the value we obtained for our central position.

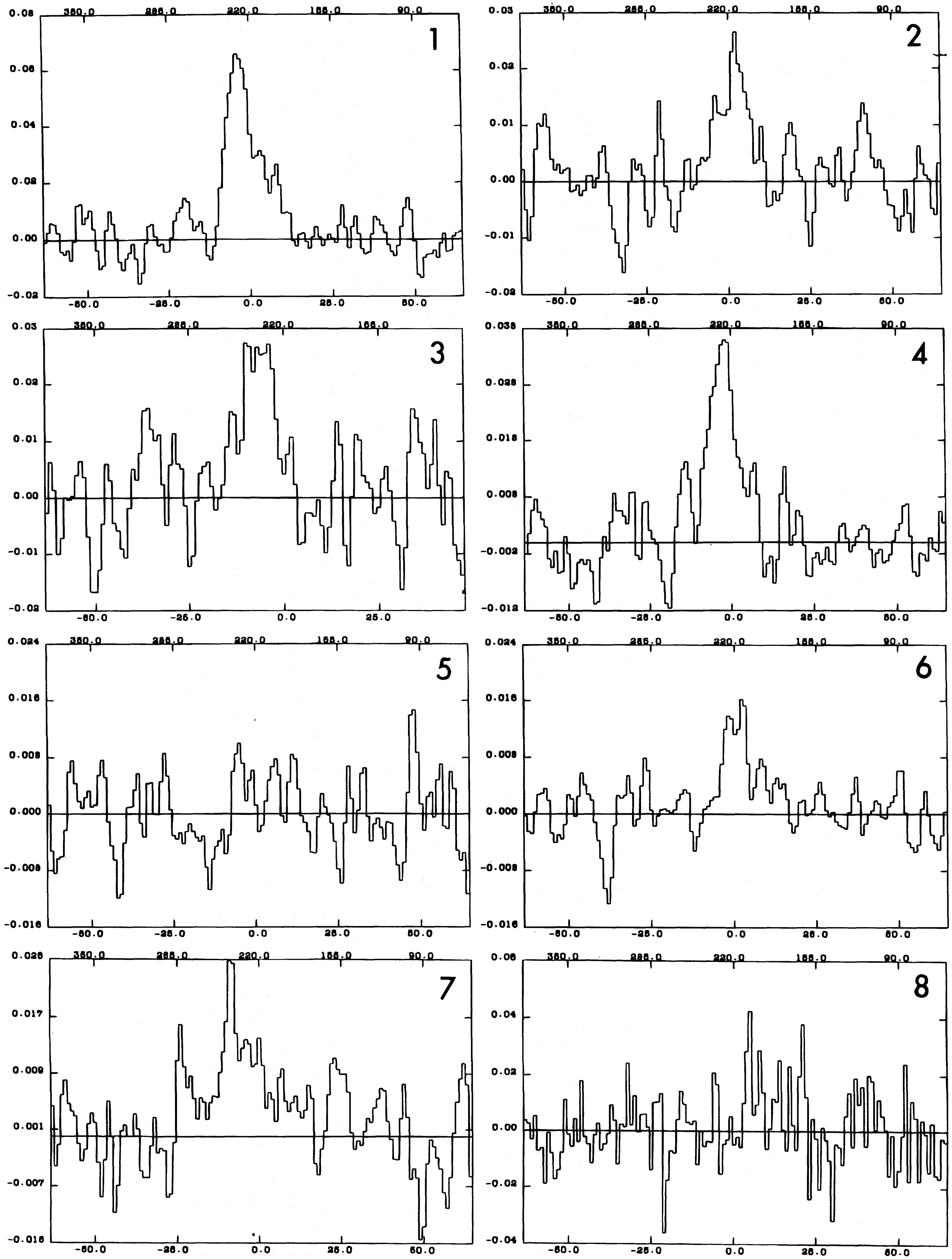

FIG. 2.—CO spectra for each of the eight observations. Velocity is plotted along the top horizontal axis in km s^{-1} and channel number along the bottom horizontal axis. The vertical axis is T_R^*. The numbers correspond to the region identifications in Fig. 1.

The masses of molecular material that we observe in our six detected positions are of order 1.0–4.4 × 10^7 $M_\odot$. These observations represent 40–110 typical giant molecular clouds that are found in the Milky Way, according to the characteristics of giant molecular clouds summarized by Scoville & Sanders (1987). This is not a surprise, however, since our beam area is large enough to include about 1800 of these "typical" clouds (diameter ~40 pc). The area covered by the 12 m beam is comparable instead to the molecular complex associated with 30 Doradus in the LMC (Cohen et al. 1988) and the masses are comparable to the ensemble of clouds found there (3 × 10^7 $M_\odot$; Garay et al. 1993). The objects we observe in NGC 4449 are comparable to other cloud complexes found in irregulars and spirals as well. A comparison with observations in other galaxies is shown in Table 3. Because the conversion factor to H_2 masses depends on the beam size and metallicity of the galaxy, beam sizes and oxygen abundances are listed in the table as well. One can see that NGC 4449 is fairly typical of these extragalactic molecular cloud complexes, although the beam size is higher than most. Only GR8 stands out as different with a much lower molecular gas mass (Verter & Hodge 1995). We also note that the beam sizes used in observations of IC10 (Wilson & Reid 1991; Ohta et al. 1992) and NGC 6822 (Wilson 1994) are significantly smaller than that used here and hence cannot be compared with these observations. The FWHM of the CO profiles, also given in Table 3, are comparable to those seen in these same molecular cloud complexes and larger than those typically found for smaller, individual clouds and typical giant molecular clouds.

Thus, the large area covered by the telescope beam, the large masses that we measured, and the relatively high velocity dispersions suggest that we are observing molecular cloud *complexes* in NGC 4449. Furthermore, these complexes appear to be comparable in scale, mass, and velocity profile width to structures found in other nearby, late-type galaxies. These cloud complexes also appear to be the largest of such objects being found in irregular galaxies.

TABLE 2

Comparisons with H I and Hα Observations

Region	$M_{\rm H\,I}$ (10^7 $M_\odot$)	$M_{\rm H_2}/M_{\rm H\,I}$	$N_{\rm H\,I,\,max}$[a] (10^{21} cm^{-2})	$L_{\rm H\alpha}$[b] (10^{38} ergs s^{-1})	$L_{\rm H\alpha}/M_{\rm H_2}$[c] ($L_\odot$ $M_\odot^{-1}$)
1	6.4	0.69	7.3	280	0.17
2	7.2	0.19	7.1	8.0	0.015
3	7.8	0.22	8.1	89	0.14
4	9.3	0.23	10.4	190	0.23
5	5.1	≤0.10	5.6	6.2	≤0.033
6	4.2	0.23	5.2	5.7	0.015
7	7.6	0.18	7.8	11	0.021
8	7.1	≤0.15	8.0	25	≤0.063

[a] The peak column density for a beam of 6".2 × 7".4. No correction has been made for inclination of the galaxy. The H I measurements are from data by Hunter, van Woerden, & Gallagher 1996, in preparation.

[b] The Hα luminosity is corrected for interstellar extinction assuming a typical $E(B-V)$ of 0.1 for the H II regions in NGC 4449 and using the extinction curve of Schild 1977.

[c] The $L_{\rm H\alpha}$ from the previous column are divided by the solar luminosity of 3.83 × 10^{33} ergs s^{-1}.

3.2. *A Comparison with the Atomic Gas*

In the H I map outlined in Figure 1 there are approximately three distinct complexes of atomic gas that are defined by having gas column densities $N_{\rm H\,I} \geq 4 \times 10^{21}$ cm^{-2}. There are also several smaller H I peaks in the optical center of the galaxy. All but positions 5 and 6 of the CO observations are within or include part of these H I peaks. Positions 2, 3, 4 lie along the northeastern H I complex as outlined in Figure 1, position 7 engulfs the southern end of the western complex, position 8 sits in between two small complexes to the south or perhaps is in an H I minimum within a single larger complex, and, finally, position 1 at the center of the galaxy includes several H I peaks. Positions 5 and 6 by contrast were chosen to lie between these particular H I complexes. Although the outlining contour in Figure 1 is 4 × 10^{21} cm^{-2}, within the complexes densities reach about twice this in all but positions 5 and 6; the peak H I column densities are given in Table 2.

There is, of course, considerably more atomic gas within NGC 4449 possessing lower overall column densities, but we consider only H I peaks in this study. Scoville & Sanders (1987) have suggested that atomic gas at column densities above 10^{21} cm^{-2} converts to molecular form, and in some irregulars molecular gas is found associated with large H I complexes. For example, the molecular ridge associated with 30 Doradus in the LMC is accompanied by a large H I ridge as well (Cohen et al. 1988), and the CO complexes observed in the SMC are found in the regions of highest H I column densities, where $N_{\rm H\,I} \geq 10 \times 10^{21}$ cm^{-2} (Rubio et al. 1991). The H I gas associated with the giant H II region

TABLE 3

Comparisons with Observations in the Literature

Galaxy	Type[a]	D (Mpc)	$M_{\rm H_2}$ (10^7 $M_\odot$)	Size (pc)	FWHM (km s^{-1})	CO Beam (pc)	Reference	10^4 O/H	Reference
LMC–30 Doradus	Im	0.051	3	...	27	130	1	2.0	9
SMC	Im	0.058	0.3–4	...	...	150	2	1.1	10
GR8	Im	1	(0.002)	...	...	145	3	0.3	11
NGC 55	Scd	2	8	390 × 975	35	420	4	2.2	12
NGC 3077	Amorphous	3.25	1	320	22–38	205	5	10.5	3
NGC 4214	Im	5.4	several	700 × 1000	...	340	6	3.6	13
NGC 4449	Im	5.4	1–4	...	11–23	1700	7	4.1	13
M101–NGC 5461	Sc	6.8	1–10	...	21	2200	8	4.2	14

[a] Morphological types for NGC 55, M101, and NGC 3077 come from Sandage & Tammann 1981.

References—(1) Garay et al. 1993; (2) Rubio et al. 1991; (3) Verter & Hodge 1995; (4) Dettmar & Heithausen 1989; (5) Becker et al. 1989; (6) Becker et al. 1995; (7) this paper; (8) Blitz et al. 1981; (9) Mathis et al. 1985; (10) Peimbert & Torres-Peimbert 1976; (11) Skillman et al. 1988; (12) Talent 1980; (13) Gallagher et al. 1982; (14) Rayo et al. 1982.

NGC 5461 in M101 is also dense, $N_{\rm H\,I} = 2 \times 10^{21}$ cm^{-2} (Blitz et al. 1981). And, so we expected that the high column density H I complexes in NGC 4449 might also harbor observable molecular clouds, which has proven to be the case.

Not unexpectedly, the positions selected to lie between the H I peaks have lower molecular gas masses and column densities than those centered on parts of dense H I complexes by factors of a few, and CO observations of two of these positions are given as upper limits only. Excluding the upper limits, the ratio of the molecular gas mass to H I gas mass in each region is approximately constant, except for the center of the galaxy. The average value of $M_{\rm H_2}/M_{\rm H\,I}$ outside the center is 0.21 ± 0.02. The center of the galaxy has a ratio about 3.5 times higher. This can be seen in Figure 3, where the ratio $M_{\rm H_2}/M_{\rm H\,I}$ is plotted against the Hα luminosity over the same region.

The values of the ratio $M_{\rm H_2}/M_{\rm H\,I}$ in NGC 4449 are different from that which is seen in several other molecular complexes in nearby galaxies. In M101 the giant H II region NGC 5461 has a ratio of molecular to atomic gas of 0.4–4 (Blitz et al. 1981) and the molecular complex in NGC 55 is almost entirely molecular gas, having 5 times more molecular gas as atomic (Dettmar & Heithausen 1989). The gas ridge containing 30 Doradus in the LMC is more like NGC 4449. There the ratio of molecular to atomic gas is 0.5 (Cohen, Montani, & Rubio 1984), which is about twice what we find in NGC 4449.

Rubio et al. (1991) have suggested that in low-metallicity galaxies the molecular clouds are the dense cores of large, massive atomic gas complexes. The density at which the atomic gas becomes molecular is determined by the density at which the gas is sufficiently shielded from the ambient UV radiation field. In the SMC Rubio et al. predicted that this critical column density is 8×10^{21} cm^{-2} and in fact CO was detected primarily in regions where $N_{\rm H\,I} \geq 10^{22}$ cm^{-2}. If for NGC 4449 we assume that the atomic gas volume density and photodissociation rates are the same as they are in the Milky Way, the equation given by Elmegreen (1989) tells us that the critical atomic gas density for a galaxy with a metallicity that is half solar is 7×10^{20} cm^{-2}. That is, molecular gas should be found in atomic clouds at densities above this value. And indeed, the H I complexes outlined in Figure 1 have column densities $\geq 4 \times 10^{21}$ cm^{-2}. Even positions 5 and 6, lying between the complexes, have a small amount of atomic gas at densities above this value. We have not observed the entire disk of NGC 4449 in CO, so we cannot say whether molecular gas is found at lower H I column densities. However, given the association of dense H I gas with our molecular observations, it seems likely that NGC 4449 is another example of a galaxy in which the molecular clouds are protected by dense H I from UV radiation.

3.3. *A Comparison with the Star Formation Activity*

The target CO positions were also chosen to cover a range in star formation activities, and the Hα luminosities in the regions of the CO observations cover 6–280 × 10^{38} ergs s^{-1} (equivalent to 58–2700 O7 V stars; Panagia 1973). The central position has the highest Hα luminosity, and positions 3 and 4 sit along the northeastern "T" of H II regions. By contrast, positions 2, 5, 6, 7, and 8 sit in regions with few high surface brightness H II regions. In fact, most of the ionized gas associated with positions 5 and 6 is probably diffuse gas not associated with local star formation. Far-infrared observations taken at 100 and 150 μm show that the Hα images are reliably tracing the massive star formation (Thronson et al. 1987). That is, regions do not show up in the far-infrared that are not also bright in Hα. Thus, we take the Hα luminosity as a measure of the massive, and by extension total, star formation activity in the region of each CO observation.

In spite of the range in star formation activity the H_2 masses inferred from the CO observations are similar from

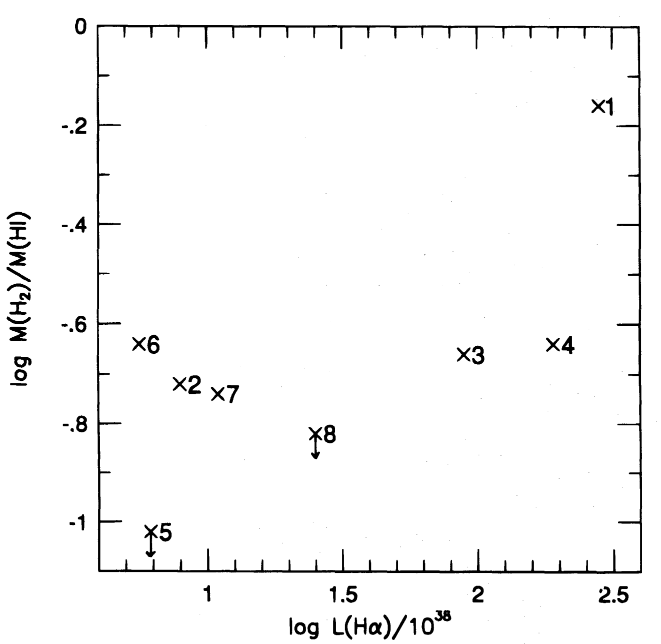

FIG. 3.—Ratio of molecular to atomic gas mass vs. the Hα luminosity in each of the eight regions identified in Fig. 1. The numbers refer to the numbers used in Fig. 1.

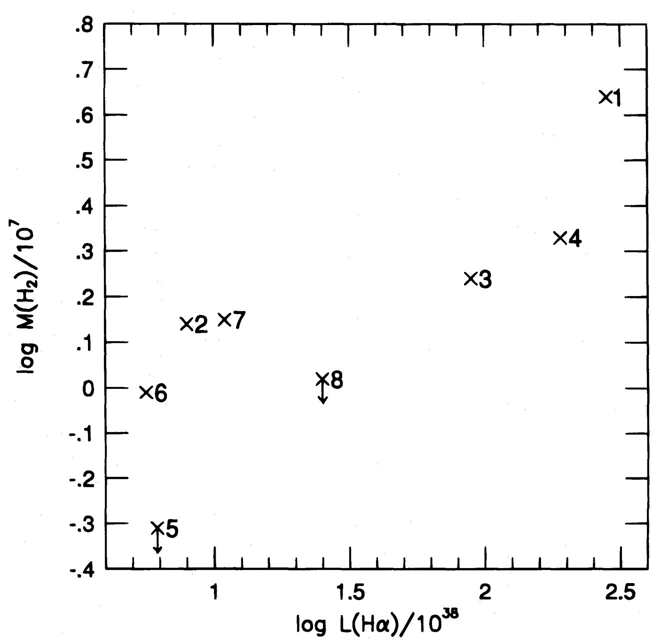

FIG. 4.—Molecular gas mass vs. the Hα luminosity in each of the eight regions identified in Fig. 1. The numbers refer to the numbers used in Fig. 1.

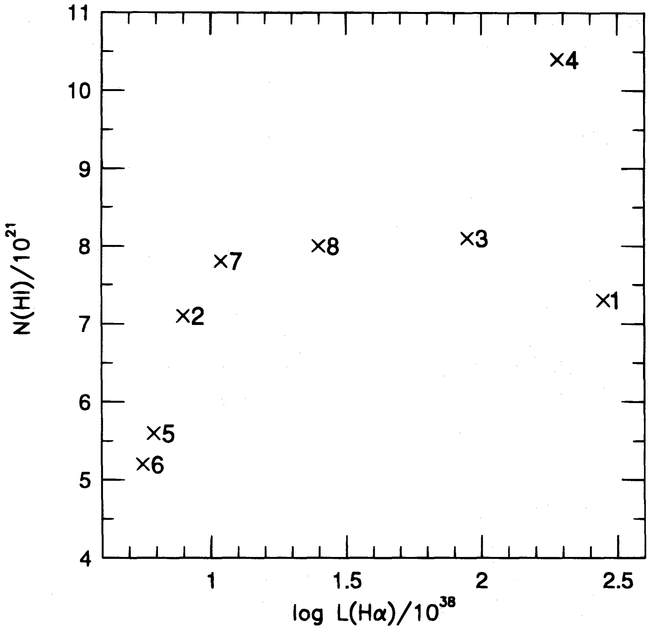

FIG. 5.—Peak H I column density vs. the Hα luminosity in each of the eight regions identified in Fig. 1. The telescope beam was 6″.2 × 7″.4, and no correction is made for galaxy inclination. The numbers refer to the numbers used in Fig. 1.

region to region, again except for the extreme positions at the center of the galaxy and number 5. This can be seen in Figure 4. There is a suggestion of a trend of higher molecular gas mass accompanying higher star formation activity, but the variation is only a factor of 2 except for the center. Similarity is also seen in the peak atomic column densities shown in Figure 5. Furthermore, we saw in the previous section that the ratios of molecular gas to atomic gas exhibit no significant trend with star formation activity. Thus, we see high column density H I complexes that contain molecular gas with similar average characteristics and yet exhibit considerably different levels of star formation activity. There might, of course, be higher dust extinction in regions of higher H_2, which would in turn make the Hα luminosity that we measure preferentially lower in these regions compared to the regions with lower H I and H_2. However, the far-infrared measurements of Thronson et al. (1987) make large differences unlikely.

A similar result is seen in the molecular gas complex in NGC 4214, where Becker et al. (1995) find that the western part of the complex has no associated Hα emission while the eastern part covers the very high star formation activity of the center of the galaxy. This is also in keeping with the statement by Scoville & Sanders (1987) that there are many giant molecular clouds in our Galaxy that do not contain H II regions, or at least giant H II regions. Scoville & Sanders go further and suggest that cloud characteristics other than size or an external stimulus are necessary to allow a giant molecular cloud to form massive stars. In this view then, it is not a surprise that parts of dense H I complexes would be vigorously forming massive stars and other parts would show no detectable signs of recent star formation. We see that these inactive molecular complexes have comparable masses, column densities, and molecular-to-atomic gas ratios. This would suggest that they have yet to engage in star formation. However, if Scoville & Sanders are correct, there is no guarantee that they will ever become active star formers.

4. SUMMARY

We have presented observations of CO emission in the active star-forming irregular galaxy NGC 4449. Within a beam of 1.7 kpc diameter, we detected 1–4 × 10^7 $M_\odot$ of M_{H_2} in six of the eight positions that we observed. Five of the observations coincided with H I complexes where the column density of the gas is ≥ 4 × 10^{21} cm^{-2}. Two positions were selected to sample the regions between these complexes, and a third straddles two H I complexes. For two of these three positions, we have only upper limits to the CO flux. The positions also sample a range in levels of star formation activity. We have found the following:

1. The size of the telescope beam, the high masses of molecular material, and the relatively high-velocity dispersions observed suggest that we have detected molecular cloud complexes. Their properties are similar to those found in other nearby, late-type galaxies.
2. The molecular mass varies by only a factor of 4 among the six reliably detected positions and by only a factor of 2 when the center is excluded. The molecular and atomic gas column densities are also similar. The center of the galaxy has a higher molecular gas mass and higher star formation activity.
3. The ratio $M_{H_2}/M_{H\,I}$ is approximately constant except for the center, and the low value shows that the molecular complexes are associated with considerable atomic gas.
4. The molecular-to-atomic gas mass ratios and high H I column densities are consistent with the picture that the molecular material is protected from UV radiation by atomic material.
5. Positions with few or no bright H II regions have molecular gas masses and gas column densities either comparable to or within a factor of a few of those regions that contain many sites of star formation. It is likely that the inactive regions have yet to engage in recent observable star formation, but it is not clear whether they ever will.

How typical of irregular galaxies is NGC 4449? It has a star formation rate that is not unusual, but which is at the high end of the range of star formation rates seen in irregulars (Hunter & Gallagher 1986). Appropriately, the oxygen abundance is also somewhat higher than that measured in many less active star-forming irregulars. However, there is some evidence that this galaxy is not as typical of irregulars as once was believed (Hunter et al. 1996, in preparation), and the H I complexes discussed here may be a manifestation of that. However, there is increasing evidence that in the environment of irregular galaxies the atomic gas plays a very important role in protecting the molecular material from UV radiation. NGC 4449 is seen to share this important feature.

We would like to thank the staff of the NRAO 12 m telescope who helped make these observations possible, and Fran Verter for very useful and entertaining comments on the manuscript. This work was supported by the Lowell Research Fund.

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