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CO EMISSION FROM THE STAR-BURST IRREGULAR GALAXY NGC 1569

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ABSTRACT

CO emission has been detected in the irregular galaxy NGC 1569 using the 14 m telescope of the Five College Radio Astronomy Observatory. The central 1 kpc of this galaxy contains approximately $7 \times 10^6 M_\odot$ of H_2 and $1 \times 10^7 M_\odot$ of H I. Comparing NGC 1569 with the Scd galaxy IC 342, both of which are at roughly the same distance, the central regions have similar blue luminosities ($\sim 2 \times 10^9 L_\odot$), but NGC 1569 has a factor of 32 *less* CO. In order to form such a luminous region with a small supply of molecular gas, either the present burst of star formation in NGC 1569 must be very efficient and of short duration or the atomic hydrogen in the outer part of the galaxy must be resupplying the central region.

Subject headings: galaxies: individual — interstellar: molecules — stars: formation

I. INTRODUCTION

In the disk of the Milky Way galaxy, molecular clouds are the potential birth sites of future generations of stars. On the local scale, there is a close relationship between regions of intense CO emission and major centers of star formation (OB associations; H II complexes; young star clusters). This correspondence led to early observations of CO in actively star-forming galaxies such as NGC 253 and M82 (Rickard *et al.* 1977). More recent observations of the molecular contents of late-type galaxies indicate several regularities in the star-forming properties of normal Sc galaxies. First, the CO radial distributions follow the exponential blue luminosity profiles in the disks of IC 342, NGC 6946, and M51 (Young and Scoville 1982*a*; Scoville and Young 1983). Second, the CO luminosities of the central 5 kpc in a sample of Sc galaxies were found to be directly proportional to the blue luminosities in the same regions (Young and Scoville 1982*b*). To the degree that the blue luminosity is from Population I stars, both of these observations suggest that more star formation occurs when more molecular gas is present, or that the star formation rate per H_2 nucleon in Sc galaxies is constant.

For irregular galaxies, however, the link between CO luminosity and the large-scale star formation properties remains less clear. In particular, irregular galaxies often display high star formation rates and other young structural features such as superassociation OB–H II complexes in common with spiral galaxies (Hunter, Gallagher, and Rautenkranz 1982; Hunter 1982*a*, *b*), but most irregular galaxies have proven surprisingly deficient in ^{12}CO $J = 1 \rightarrow 0$ line emission. The only irregular galaxy which displays intense CO emission is the unusual galaxy M82 (Rickard *et al.* 1977; Stark 1982; Young and Scoville 1984). Elmegreen, Elmegreen, and Morris (1980) surveyed six of the nearer northern Magellanic type irregular galaxies with negative results at a sensitivity level of $I_{CO} \sim 1.5$ km s^{-1} (for a line 100 km s^{-1} across), which led them to conclude that the CO surface brightness of these galaxies must be considerably below that of luminous spirals. Similar but somewhat less stringent limits have been set by Gordon, Heidmann, and Epstein (1982) in the extraordinary high star formation rate "clumpy irregular" galaxies. In fact, the only CO detections in Magellanic type irregular galaxies are limited to the Large Magellanic Cloud (Huggins *et al.* 1975; Israel *et al.* 1982) and low signal-to-noise measurements by Rowan-Robinson, Phillips, and White (1980).

In order to more clearly define the relationship between CO luminosity and star formation processes in irregular galaxies, a program was undertaken to measure ^{12}CO $J = 1 \rightarrow 0$ emission from NGC 1569 (also known as VII Zw 16). Although this galaxy is experiencing a major burst of star formation (de Vaucouleurs, de Vaucouleurs, and Pence 1974; Hodge 1974; Hunter, Gallagher, and Rautenkranz 1982; Hunter 1982*a*), there can be little doubt that NGC 1569 has the kinematic properties which place it in the irregular structural class (Tully *et al.* 1978; Reakes 1980; cf. Goad and Roberts 1981). In addition, recent observations by the *Infrared Astronomy Satellite* (*IRAS*) indicate that NGC 1569 is a strong source of far-infrared emission. This object thus provides an excellent opportunity to make an accurate measurement of the CO surface brightness of an irregular galaxy.

II. OBSERVATIONS AND RESULTS

CO observations of the center of NGC 1569 were made in 1982 February with the 14 m telescope of the Five College Radio Astronomy Observatory (FCRAO)[4] and a cooled mixer receiver with a single sideband temperature of 250 K. At the CO $J = 1 \rightarrow 0$ frequency (115.2712 GHz) used for the measurements, the telescope half-power beamwidth is 50″, which corresponds to a diameter of 1.1 kpc at the adopted distance of 4.7 Mpc for NGC 1569 (Hunter, Gallagher, and Rautenkranz 1982). A comparison with the Hα intensity maps in Hunter (1982*a*, *b*) shows that the beam includes the three major H II complexes in the galaxy.

Data were obtained by position switching every 30 s to a position 8′ from the nucleus for a total of 3 hours of integration on the galaxy. The intensity calibration procedure,

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described in detail in Young and Scoville (1982*a*), yields a temperature scale T_A^* such that, for an extended source, the intensity will equal that obtained on the 11 m telescope (Ulich and Haas 1976), while for a point source, T_A^* will be a factor 1.6 higher, as expected given our smaller beam size. On this scale, the center of the Orion nebula (KL) has $T_A^*(\mathrm{CO}) = 62$ K.

The resulting CO spectrum, smoothed to 15 km s^{-1}, is shown in Figure 1. The integrated intensity (I_{CO}) is 1.1 K km s^{-1}, while the 1 σ uncertainty on this intensity is 0.2 K km s^{-1}. Thus, the signal is a 5 σ detection and would lie slightly below typical upper limits set by Elmegreen, Elmegreen, and Morris (1980). Also illustrated in Figure 1 is the H I profile of Reakes (1980) which has a virtually identical velocity structure to the CO emission. This correlation indicates the rotation curve has reached its maximum velocity in the central region. Note that the galactic absorption is seen in both the CO and H I spectra; Hunter (1982*a*, *b*) finds that the H II regions in NGC 1569 lie in the local standard of rest (LSR) velocity range of -60 to -90 km s^{-1} which is unaffected by galactic absorption. The adopted parameters for NGC 1569 are listed in Table 1.

TABLE 1

NGC 1569 PARAMETERS

R.A. (1950)[a]	$4^h26^m5\overset{s}{.}8$
Decl. (1950)[a]	$64°44'18\overset{''}{.}5$
V_{SUN}[b]	-83 km s^{-1}
Classification[c]	IBm IV
Distance[a]	4.7 Mpc
50″ on galaxy	1.14 kpc
Inclination[d]	63°
Position angle[d]	116°
D_{25}[e]	$2\overset{'}{.}75$
Total M(H I)[f]	$3.8 \times 10^8 M_\odot$
Total luminosity[d]	$2.8 \times 10^9 L_\odot$

[a] Hunter, Gallagher, and Rautenkranz 1982.

[b] Heliocentric velocity of -83 km s^{-1} (Sandage and Tammann 1980, hereafter RSA) corresponds to V_{LSR} of -101 km s^{-1}.

[c] Type from de Vaucouleurs, de Vaucouleurs, and Corwin (1976, hereafter RC2); luminosity class from RSA.

[d] Ables 1971.

[e] RC2.

[f] Reakes 1980.

a) *Mass of* H$_2$

An estimate of the molecular mass in the central region of NGC 1569 can be found by using the CO to H$_2$ conversion of 4×10^{20} H$_2$ cm^{-2} (K km s^{-1})$^{-1}$ derived from observations of dark clouds and giant molecular clouds in the Milky Way (see the Appendix of Young and Scoville 1982*a*). The observed surface density of hydrogen in molecular form is given by equation (3a) of Young and Scoville (1982*a*), or

$$N(\mathrm{H_2}) = 4 \times 10^{20}\, I_{\mathrm{CO}}[\mathrm{H_2\ cm^{-2}/(K\ km\ s^{-1})}] . \quad (1)$$

In NGC 1569, $I_{\mathrm{CO}} = 1.1$ K km s^{-1}, which translates into an observed surface density of 9×10^{20} H cm^{-2} in molecular form.[5] This estimate for the molecular surface density is slightly less than the surface density of 1.5×10^{21} atoms cm^{-2} which Reakes (1980) found in H I with a 2′ beam. The interstellar medium masses in the central 50″ are approximately 7×10^6 $M_\odot$ of H$_2$ and 10^7 $M_\odot$ of H I (assuming a flat H I distribution across the central 2′).

In order to compare the CO properties of NGC 1569 with regions of the same size in late-type spirals, we consider two regions in the nearby Scd galaxy IC 342 ($D = 4.5$ Mpc, which is roughly the same distance as NGC 1569). Ables (1971) has determined the B luminosity profiles for both of these galaxies; in the central 1 kpc, the luminosities are 1.5×10^9 $L_\odot$ and 1.8×10^9 $L_\odot$ for IC 342 and NGC 1569 respectively. Although these regions have similar B luminosities, IC 342 has 32 times more CO at its center than does NGC 1569! It is also instructive to compare the disk of IC 342 with the center of NGC 1569 since spiral disks and irregular galaxies both have

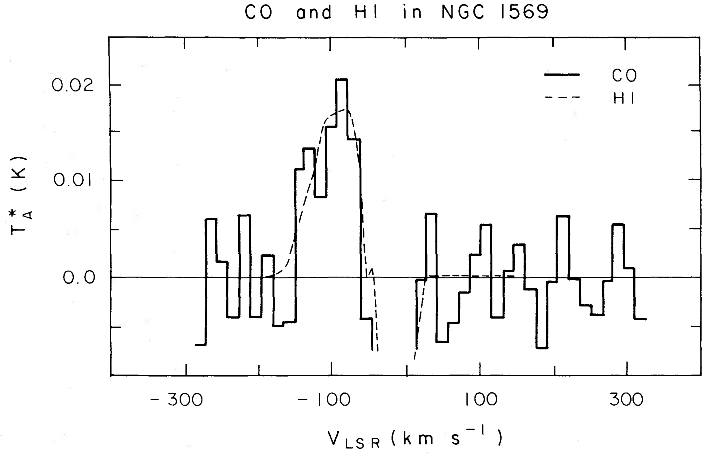

FIG. 1.—Spectrum of CO emission toward the center of NGC 1569 (*solid histogram*) smoothed to 15 km s^{-1} resolution. The H I profile of the galaxy (*dashed line*) is from Reakes (1980). Both the CO and H I profiles show the presence of local gas in the reference position between velocities of -40 and $+10$ km s^{-1}.

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[5] If the CO ratio in NGC 1569 is low relative to that in our galaxy, then this estimate of the H$_2$ surface density is a *lower* limit. Hunter, Gallagher, and Rautenkranz (1982) find the oxygen gas-phase abundance in NGC 1569 is approximately one-fourth of the solar abundance, and if the CO abundance is similarly low, then the amount of H$_2$ present could be somewhat higher.

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comparatively low stellar and gas densities. At a point 6 kpc out in the disk of IC 342, $I_{\rm CO} = 1.6$ K km s^{-1} (Young and Scoville 1982*a*) and $L_B = 5 \times 10^7 L_\odot$ (Ables 1971). Thus, in the region of IC 342 where $I_{\rm CO}$ is comparable to the value in the center of NGC 1569, the *B* luminosity is lower by a factor of 26. Therefore, the comparison with IC 342 indicates that NGC 1569 is deficient in CO relative to a region of similar blue luminosity, and it is excessively luminous in the blue relative to a region of similar CO luminosity.

Table 2 summarizes the comparisons between NGC 1569 and IC 342, where the H_2 masses were derived assuming a linear dependence of H_2 surface density on CO intensity (see eq. [1]). Whereas the nucleus and disk of IC 342 have similar values for $M(H_2)/L_B$ of 0.16 and 0.17 $M_\odot/L_\odot$ respectively, NGC 1569 has a face-on value of 0.0037 $M_\odot/L_\odot$ or a factor of 45 *less*. In a sample of Sc galaxies, Young and Scoville (1982*b*) found a mean value of $M(H_2)/L_B = 0.17 \pm 0.08\ M_\odot/L_\odot$ for the CO to blue luminosity ratio of the central 5 kpc. While the data discussed above for the nucleus and disk of IC 342 are consistent with the results for the Sc sample, NGC 1569 shows no resemblance to the properties of the Sc galaxies. If the *B* luminosity is a measure of star formation averaged over the last 2×10^9 years, then NGC 1569 has a factor of approximately 45 *more* star formation per unit H_2 than the Sc galaxies.

Within the Sc sample studied by Young and Scoville, the H_2/H I ratio in the central 5 kpc was found to vary from ≥ 30 for the high-luminosity galaxies to less than 0.5 for the low-luminosity galaxies. The observed surface densities of both H I and H_2 in NGC 1569 are comparable to those observed in the low-luminosity Sc galaxies, and the H_2/H I mass ratio of 0.6 is also similar to the value observed for these galaxies. In addition to the low central H_2 mass in NGC 1569, it has a low dynamical mass in the inner 1 kpc. This results in a value of $M_{\rm dyn}/L_B = 0.07\ M_\odot/L_\odot$ in the central 1 kpc for NGC 1569 relative to a value of 1 $M_\odot/L_\odot$ for IC 342.

b) CO *and Star Formation in Irregular Galaxies*

From the present and previous CO studies of irregular galaxies, it is clear that these systems as a class are deficient in CO emission relative to regions in spiral galaxies with similar luminosities and stellar content. Elmegreen, Elmegreen, and Morris (1980) have recognized this problem and considered its resolution in terms of possible environmentally imposed differences in CO excitation and abundance. While abundances may be low in some instances, including NGC 1569, the luminous clumpy irregular galaxies have near solar gas oxygen abundances (Boesgaard, Edwards, and Heidmann 1982; Gallagher and Hunter 1984) but still show CO deficiencies relative to spiral galaxies. The possibility that the CO content is normal but is radiating less efficiently, because of a decrease in cosmic-ray heating in irregular galaxies, in principle remains a viable explanation. There are, however, other indications of a true absence of widespread surface coverage by molecular clouds in irregular systems. The optical imaging reported by Hunter (1982*a*, *b*) showed that large dark clouds are rare in irregular galaxies and that very few of these are sufficiently optically thick to hide extensive amounts of molecular matter (see Elmegreen 1980; Gallagher and Hunter 1981). It therefore appears that large, relatively quiescent molecular cloud complexes are not a feature of irregular galaxies. On the other hand, the presence of OB associations with normal structural characteristics in these galaxies suggests, as does the detection of water masers around LMC star formation sites (Scalise and Braz 1980), that on local scales the molecular clouds are normal.

In order for this small amount of H_2 in NGC 1569 to be responsible for abundant star formation, either the present burst of star formation must be very efficient and of short duration or the H I in the outer parts is probably being recycled into the center. Alternatively, the abundant star formation could have disrupted the parent molecular clouds, thus reducing the observed molecular content. Hunter, Gallagher, and Rautenkranz (1982) have estimated that the star formation rate in NGC 1569 is 0.4 $M_\odot$ yr^{-1}, and considering the total available gas supply in NGC 1569 of $3.8 \times 10^8\ M_\odot$ of H I over a region 6′ across, the present rate can be maintained for only about 10^9 years. If this rate of star formation were to persist over a long period of time, there would be more old stars as well as higher metallicities in NGC 1569.

TABLE 2

COMPARISON OF REGIONS 1 kpc ACROSS IN NGC 1569 AND IC 342

Parameter	NGC 1569	IC 342 Center	IC 342 Disk
L_B[a]	$1.8 \times 10^9\ L_\odot$	$1.4 \times 10^9\ L_\odot$	$5.1 \times 10^7\ L_\odot$
$M(H_2)$[b]	$6.7 \times 10^6\ M_\odot$	$2.3 \times 10^8\ M_\odot$	$8.9 \times 10^6\ M_\odot$
M(H I)[c]	$1.1 \times 10^7\ M_\odot$	$3.9 \times 10^6\ M_\odot$	$5.6 \times 10^6\ M_\odot$
$M(H_2)/L_B$	$0.0037\ M_\odot/L_\odot$	$0.16 \times M_\odot/L_\odot$	$0.17 \times M_\odot/L_\odot$
$V_{\rm obs}$[d]	27 km s^{-1}	75 km s^{-1}	...
$M_{\rm dyn}$	$1.2 \times 10^8\ M_\odot$	$1.4 \times 10^9\ M_\odot$	...
$M_{\rm dyn}/L_B$	$0.07\ M_\odot/L_\odot$	$1\ M_\odot/L_\odot$	...
$M(H_2 + $ H I$)/M_{\rm dyn}$	15%	17%	...

[a] Luminosities from M_B in 50″ and A_B (Ables 1971); $M_B(0) = 5.48$.

[b] See eq. (1).

[c] H I from Reakes 1980 and Rogstad and Shostak 1972 for NGC 1569 and IC 342 respectively.

[d] $V_{\rm obs}$ is the rotational velocity observed at a radius of 0.5 kpc, from this work and Rogstad and Shostak 1972 for NGC 1569 and IC 342 respectively.

[e] Dynamical mass in $M_\odot$ calculated assuming $M_{\rm dyn} \sim 2.25 \times 10^5\ RV^2$, for R in kpc and V in km s^{-1}.

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c) Interstellar Medium in Irregular Galaxies

Irregular galaxies provide an alternative gas-rich galactic environment to that found in the disks of luminous spirals in which to investigate star formation. However, there are several reasons why one might expect the interstellar medium in irregular galaxies to differ from that in spiral galaxies. First, low rotational velocities in irregular galaxies eliminate the possibility of large-scale gas shocks induced by spiral arms (Strom 1980). This feature, in combination with the small sizes of most irregular galaxies, also results in specific angular momenta in the gas which are approximately 10 times smaller than in spiral galaxies. This may significantly impact the stability of gas clouds (see Mouschovias 1981). A second difference could result from the fact that, in an average sense, the *volume* gas density in irregular galaxies is lower relative to the projected gas surface density than in spiral galaxies. This point follows from the observed constancy of H I global velocity dispersions in most types of galaxies (Allsopp 1978), in which case the gas scale height is proportional to the reciprocal of the disk mass density. Since irregular galaxies have lower total disk mass densities than spiral galaxies, they must also have larger scale heights and lower volume densities. Thicker disks may also indirectly affect star formation rates (e.g., if propagating star formation is a factor, then these galaxies have higher dimensionality which can lead to higher relative amounts of star formation [Seiden, Schulman, and Gerola 1979]). A third difference between spiral and irregular galaxies could be that, since irregular galaxy disks have lower densities and binding energies, they are more easily perturbed by energy inputs from stars. This can affect large-scale magnetic field strengths and configurations, cosmic-ray fluxes, and relative fractions of interstellar matter in hot and cool phases, all of which in turn can influence cloud structures (see Elmegreen, Elmegreen, and Morris 1980).

Although it remains a possibility that the CO deficiencies in irregular galaxies are related to their metallicities, more observations of both molecules and elemental abundances in irregular galaxies are necessary to determine the extent of this effect.

IV. CONCLUSIONS

1. CO has been detected in the irregular galaxy NGC 1569, with a velocity structure similar to that observed in H I.
2. Relative to the center of the Sc galaxy IC 342, NGC 1569 has a similar B luminosity in the central 1 kpc but a factor of 32 less CO.
3. The ratio of $M(H_2)/L_B$ in the central 1 kpc (corrected to face-on) is 0.0037 $M_\odot/L_\odot$, which is a factor of 40 lower than the value found in the center of IC 342 and other Sc galaxies.
4. The high luminosity in NGC 1569 resulting from a small supply of molecular gas suggests that either the present burst of star formation must be very efficient and of short duration or the atomic hydrogen in the outer parts is being recycled into the center.

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