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Research Note

A Survey of Nearby Galaxies for CO

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Summary. We have made a survey of the nuclei of 81 galaxies for the 1–0 line of CO. 38 of the galaxies are from a complete sample with recession velocity $\leq 400 \text{ km s}^{-1}$ and 21-cm line strength $\geq 10^{-27} \text{ W m}^{-2}$, and the remainder represent nearby galaxies with weaker or no H I, early-type galaxies (E/SO/Sa) with detected H I, and active/infrared galaxies.

Galaxies with strong CO lines like M 82, NGC 253 and IC 342 are exceedingly rare: all the galaxies we observed are weaker than 0.2 K except the irregular galaxy DDO 133 with $T_A^* = 0.22 \text{ K}$. We have new, confirmed detections of two other irregular galaxies, IC 10 and Pegasus, at a weaker level, and unconfirmed detections of the irregular NGC 3109 and the nearest Type I Seyfert galaxy NGC 4051. We have confirmed the existence of CO in the nucleus of NGC 6946 and obtained spectra of new positions in M 82 and NGC 253.

Key words: galaxies – molecules

1. Introduction

Although OH and H₂CO have been known in external galaxies for some time (Weliachew, 1971; Whiteoak and Gardner, 1973), the discovery of CO in galaxies (Rickard et al., 1975, 1977a, b; Solomon and de Zafra, 1975; Huggins et al., 1976; Morris and Lo, 1978; Combes et al., 1977, 1978) opens the way to the determination of the total mass in galaxies in the form of molecules and to direct study of star formation regions in galaxies of different types. Our approach was to study a complete sample of nearby galaxies in an effort to find the dependence on galaxy type, and other parameters, of the mass of molecules present in the central regions.

2. Observations

The observations were made during December 27–31, 1976, and September 11–15, 1977, with the NRAO 36-foot (11 m) telescope, using the cooled mixer receiver (Kerr, 1974) and the 256 × 1 MHz filterbank (Mauzy, 1974), corresponding to a velocity resolution of 2.6 km s^{-1} . In order to maintain a stable spectral baseline, an essential feature of any search for broad features, we switched the

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telescope at 10 s intervals between on and off positions separated by only 2' in azimuth (cf. 30' used by Rickard et al., 1977a). This is significantly greater than the half-width to half-power of the sources mapped by Rickard et al. in M 82 and NGC 253 (at distances $\sim 3 \text{ Mpc}$), but may be smaller than the nuclear sources in Local Group galaxies. However, the drawback of some possible contamination due to incomplete switching off a source is offset by improved baselines. Baseline stability was also helped by observing the source close to transit, where possible. The observations were chopperwheel calibrated and reduced to beam-diluted brightness temperatures T_A^* using the method of Ulich and Haas (1976). The temperature scale was checked by occasionally observing the Ulich and Haas single-sideband calibrated sources, and the pointing accuracy checked by making five-point maps of Jupiter. The telescope beam has a half-power width of $\sim 65''$ at 2.6 mm.

Our main observing list comprised non-Virgo cluster galaxies with recession velocity corrected for galactic rotation $v_0 \leq 400 \text{ km s}^{-1}$ (with a Hubble constant of $50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, assumed throughout this paper, this corresponds to galaxies within 8 Mpc), $\delta > -30^\circ$, and with 21-cm line strengths $\geq 10^{-27} \text{ W m}^{-2}$. 48 such galaxies are given in the Second Reference Catalogue of Bright Galaxies (de Vaucouleurs et al., 1976): we observed 38 of these and the remaining 10 have been observed by Rickard et al. (1977a) and Morris and Lo (1978). We have also observed 8 out of 15 galaxies with $v_0 \leq 400 \text{ km s}^{-1}$, $\delta > -30^\circ$, and weaker 21-cm line emission, and 5 of the 12 galaxies with $v_0 \leq 400 \text{ km s}^{-1}$, $\delta > -30^\circ$, and no detected 21-cm emission, which have reliable nuclear positions. We have also observed 18 early-type galaxies (E/SO/Sa) which have been detected in H I, 10 active/infrared galaxies and NGC 1156 and 7640. Thus our sample covers the complete range of galaxy type and 21-cm line strength.

3. Analysis

After removal of the outermost 30 channels (which tend to be noisy and unreliable), a few noise spikes ($> 5\sigma$) and defective channels, we tested the linearity of our baselines by fitting parabolas to the outer portions of our spectra, rejecting scans which showed excessive curvature or excessive noise. No scans had to be rejected for the March 1976 run, but worse weather meant that 30% of scans taken in September 1977 were rejected. We then tested our averaged spectra for an individual galaxy for the presence of a Gaussian line centred on the assumed recession velocity of the galaxy, using a variety of assumptions about the line width (e.g. $\Delta v = 50, 100, 300 \text{ km s}^{-1}$, $\Delta v = 21\text{-cm line width}$). Apart from the cases discussed below, no lines were detected. Our

Table 1. Galaxies not detected in CO

N 205, N 224 (= M 31), IC 1574, N 244, N 247, IC 1613, N 1023, N 1156, N 1275, Haro 20, IC 356, N 1569, N 1560, 3C 120, N 1614, II Zw 40, N 2366, DDO 43, DDO 46, DDO 47, Hol II, DDO 52, N 2655, N 2683, N 2685, N 2782, N 2798, Hol I, DDO 69, Sex B, N 3077, Sex A, Mk 33, N 3718, Mk 178, N 3870, DDO 99, N 4144, N 4151, N 4192, N 4194, N 4203, N 4214, N 4236, N 4244, DDO 126, DDO 125, N 4449, DDO 127, N 4458, N 4526, N 4552, N 4621, DDO 165, DDO 168, N 5128, N 5204, DDO 185, DDO 190, N 5631, DDO 194, N 5846, N 6340, N 6822, N 6835, DDO 210, N 7013, N 7332, N 7468, N 7625, N 7640, Wolf-Lundmark.

$3-\sigma$ upper limits for T_A^* are ≤ 0.2 K in all cases and ≤ 0.1 K for about half the galaxies observed. Our main result is therefore that galaxies with strong CO lines like M 82, NGC 253 and IC 342 are exceedingly rare. The list of galaxies from which nuclear emission was not detected is given in Table 1. The nuclear positions were mainly taken from Gallouet et al. (1971, 1973, 1976) or Fisher and Tully (1975).

4. Discussion of Individual Galaxies

The spectra of the galaxies we detected are shown in Fig. 1. The best fitting Gaussian lines of halfwidth Δv equal to the corresponding H I line width are shown for comparison. Our spectra are not of sufficient quality for a reliable determination of the CO line width.

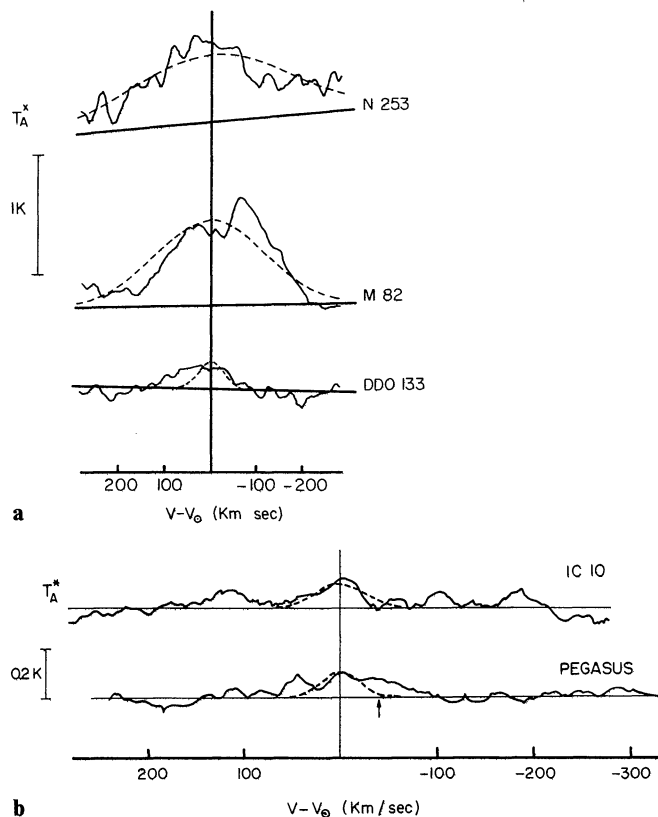


Fig. 1. Averaged CO spectra for **a** N 253, M 82 and DDO 133, **b** IC 10 and Pegasus. The spectra have been smoothed with a Gaussian of halfwidth 20 km s^{-1} . The best-fitting Gaussian lines of halfwidth equal to the 21-cm width are shown as broken lines

M 82 (NGC 3034)

This was first detected in CO by Rickard et al. (1975) and has been mapped by Rickard et al. (1975, 1977a). Gallouet and Heidmann (1971) and Dressel and Condon (1976) give positions for the optical nucleus of M 82 differing by $31''$, so we took spectra at both positions. At the Dressel and Condon position we obtained a strong symmetric profile (Fig. 1a) and comparison with the data of Rickard et al. (1977a) suggests that this position is close to the centre of the molecular distribution. The spectrum at the Gallouet and Heidmann position was weaker and asymmetrical, in accordance with the model of Rickard et al. (1977a).

NGC 253

This was also first detected by Rickard et al. (1975) and mapped by Rickard et al. (1975, 1977a). We selected a position close to the peak of the Rickard et al. (1977a) map. Again we obtained a symmetrical profile (Fig. 1a), rather stronger than the intensities at adjacent points obtained by Rickard et al. (1977a), so that we are close to the centre of the molecular distribution.

DDO 133

Although this galaxy was observed during one run only (March, 1976), the strength of the CO line (7.5σ) is sufficient to make the detection reasonably certain. The CO spectrum of this dwarf irregular (Fig. 1a) suggests that the velocity width in CO may be broader than the H I width of 62 km s^{-1} .

Pegasus (DDO 126)

Fisher and Tully (1975) measured the 21-cm recession velocity as -179 km s^{-1} relative to the sun for this Local Group irregular (indicated by an arrow in Fig. 1b). However there appeared to be a more significant feature, seen during both observing runs, centred on -140 km s^{-1} . The emission seems broader than the H I width of 43 km s^{-1} . There is no conflict between our detection and the upper limit of Morris and Lo (1978) of 0.30 at a position $24''$ away.

IC 10

This irregular was detected during both runs and the CO line width is consistent with being the same as the 21-cm line width of 62 km s^{-1} . We also observed positions 1' N, E, S, and W of the nucleus, in September 1977, without detecting any emission. Our $3-\sigma$ upper limits at these locations are $T_A^* \leq 0.12$ K, assuming $\Delta v = 62 \text{ km s}^{-1}$. The nuclear molecular emission therefore probably has an extent no greater than 1'. Morris and Lo (1978) obtained $T_A^* \leq 0.2$ at a position $36''$ from our detection.

Table 2. De/ected galaxies

Name	Position	Ref.	v_{\odot}	$\Delta v_{\text{H I}}$	Ref.	d (Mpc)	$T_A^* \pm \sigma_T$	Δv_{CO}	$\lg M_{\text{H}_2}$
IC 10	0 17 41.5 59 0 52	(1)	-346	62	(2)	(1)	0.091 ± 0.018	~ 50	6.25
N 253	0 45 3.3 -25 33 50		250	400	(3)	3.4	0.554 ± 0.050	~ 370	9.03
M 82	9 51 45.3 69 54 11	(4)	240	273	(5)	3.25	0.701 ± 0.032	~ 270	8.95
N 3109	10 0 46.9 -25 54 47	(1)	403	123	(2)	(2.6)	$0.110 \pm 0.025^*$		(7.61)
N 4051	12 0 36.3 44 48 39	(1)	766	397	(6)	7.6	$0.098 \pm 0.024^*$		(8.97)
DDO 133	12 30 25.0 31 48 53	(7)	335	63	(7)	(6.9)	0.224 ± 0.030	~ 120	8.76
N 6946	20 33 47.7 59 58 59	(1)	50	224	(2)	11.0	0.055 ± 0.014		(8.82)
Pegasus	23 26 2.8 14 28 16	(1)	-140	43	(7)	(0.67)	0.100 ± 0.020	~ 100	6.30

* Observed during one run only, so require confirmation

Ref.

1. Galluet and Heidmann 1971, Gallouet et al. 1973, 1976
2. Dean and Davies 1975
3. Huchtmeier 1972
4. Dressel and Condon 1976
5. Weliachew 1974
6. Lewis and Davies 1973
7. Fisher and Tully 1975

NGC 6946

Morris and Lo (1978) detected the nucleus of this galaxy with $T_A^* = 0.16$, whereas Rickard et al. (1977a) give it as a negative result with $\sigma_T = 0.177$. We reobserved it, using the nuclear position of Gallouet et al. (1973), which is 1' from that used by Rickard et al. but only 15" from that used by Morris and Lo. We obtained $T_A^* = 0.055 \pm 0.014 (4.0\sigma)$ using the H I line width of 224 km s^{-1} , a positive detection but a factor 3 weaker than that found by Morris and Lo.

NGC 3109

This nearby irregular (possibly in the Local Group – Yahil et al., 1977) gave $T_A^* = 0.11 \pm 0.025 (4.4\sigma)$, but was observed only during March 1976, so requires confirmation.

NGC 4051

Although given as a negative by Rickard et al. (1977a) we thought it worthwhile to spend some time on this, the nearest Type I Seyfert galaxy, in the light of Rickard et al.'s detection of the Seyfert NGC 1068. With the 21-cm line width of 397 km s^{-1} we found $T_A^* = 0.098 \pm 0.024 (4.1\sigma)$ in March 1976, a detection not inconsistent with the earlier limit of Rickard et al. ($\sigma_T = 0.062$). However, since the assumed velocity half-width is two-thirds of the available bandwidth, we have to regard this result with some caution, and confirmation is clearly required.

5. Discussion

For each of the galaxies discussed above, we have calculated in Table 1 the mass of hydrogen molecules in our 65" beam, assuming LTE, from

$$M_{\text{H}_2} = \left[\frac{\text{H}_2}{\text{CO}} \right] m_{\text{H}_2} \left(\frac{2\pi(65'')^2}{2.35^2} \right) \left\{ \frac{2kT_{\text{ex}} e^{h\nu/kT_{\text{ex}}}}{3h\nu} \right\} \cdot \frac{8\pi k d^2 v^2 \alpha}{hc^3 A} \int T_A^* dv \quad (1)$$

where d is the distance of the galaxy, T_{ex} is the CO excitation temperature, A is the Einstein coefficient and

$$\alpha \left(\simeq \frac{T(^{13}\text{CO})}{T(^{12}\text{CO})} (^{12}\text{C}/^{13}\text{C}) \right)$$

allows for the effect of optically thick lines.

Rickard et al. (1975, 1977a, b) appear to have evaluated the expression in the curly brackets incorrectly, overestimating it by a factor of ~ 5 . This is compensated for by their assumption that $\alpha = 1$, probably a serious underestimate.

We adopt $T_{\text{ex}} = 25 \text{ K}$, a value typical of hot-centred clouds in our Galaxy; $\text{H}_2/\text{CO} = 10^{4.4}$, a compromise between the value of $10^{4.1}$ for cold clouds (Dickman, 1978) and the higher value which seems to be implied for hot-centred clouds (Blair et al., 1978; Kwan, 1978; Wootten et al., 1978; Rowan-Robinson, 1979); $\alpha = 7.5$, corresponding to $^{12}\text{C}/^{13}\text{C} = 40$ (Wannier et al., 1976), $T(^{12}\text{CO})/T(^{13}\text{CO}) \sim 5.5$, as found by Solomon et al. (1979) for clouds in our Galaxy. Then

$$M_{\text{H}_2} = 10^{5.65} T_A^* \Delta v d^2, M_{\odot} \quad (2)$$

where Δv is in km s^{-1} and d is in Mpc.

For IC 10, NGC 4051, DDO 133 and Pegasus, our beam covers $\geq 20\%$ of the galaxy's quoted optical diameter, so these mass estimates represent the total nuclear molecular mass. For M 82, NGC 253 and probably NGC 3109 and NGC 6946, the nuclear emission extends beyond our beam. In all cases except IC 10 the nuclear molecular mass amounts to $> 1\%$ of the galaxy's total virial mass, calculated from Fisher and Tully's (1975) expression, a substantially higher fraction than that of 0.2% found for our Galaxy nucleus (Banja, 1977). We find no detailed correlation between the CO line strength, $T_A^* \cdot \Delta v$, and the 21-cm line strength for the galaxies we have observed and those detected by other observers.

We also find no clear correlation between CO line strength and infrared flux, except that M 82 is exceptional both in its CO line strength and in its infrared flux.

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Note added in proof: P. J. Encrenaz et al. (1979, *Astron. Astrophys.* **78**, L1) find $\langle T(^{12}\text{CO})/T(^{13}\text{CO}) \rangle = 8.8$ for five external galaxies, giving $\alpha = 4.5$, so that our masses should be reduced by a factor 1.6.