CO IN DISTANT GALAXIES

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ABSTRACT. Studies of the central parts of nearby galaxies as well as of distant luminous galaxies, made with the IRAM 30 m telescope, show that the CO 2–1/1–0 ratio is 0.6 ± 0.2. Many galaxies in the distant luminous sample are new detections. In contrast to the distant luminous sample, the galaxy NGC 3147, at cz = 2800 km/s, has a more modest infrared luminosity, but a large mass of molecular gas, which is *not* concentrated in the center of the galaxy.

I. INTRODUCTION

New studies with the IRAM 30 m telescope have been made to detect CO in the central parts of distant galaxies, to try to get reliable CO 2–1/1–0 ratios, to sent upper limits on the sizes of the emitting regions, and to try to find the highest CO luminosities among the brightest galaxies in the far infrared. Our method has been to look among two samples: 1) a "Comparison" sample for the 2–1/1–0 ratio in nuclear regions of 27 "nearby" galaxies with $10^9 < L_{IR} < 10^{12}$ L$_\odot$, and distances < 100 Mpc (cz < 7300 km/s; H$_o$ = 75 km/s/Mpc). 2) a "Deep" sample with $L_{IR} > 10^{11}$ L$_\odot$, and distances 75 Mpc < D < 1 Gpc (5400 < cz < 75000 km/s). The latter galaxies have measured redshifts and a variety of IRAS 60/100 μm flux ratios; some are megamaser galaxies.

II. THE NEARBY NUCLEUS SAMPLE

Götz (1990), Greve and Steppe observed 20 spirals, 14 barred galaxies, 5 irregulars and 12 Arp peculiar galaxies, mostly galaxies which had been previously observed in CO(1–0) at FCRAO, NRAO or NRO. For all these galaxies new B,V,I CCD images were taken with the Calar Alto 2.2 m telescope, and new positions were derived for the I nuclei. For the CO observing with the 30 m telescope, the beams were 21$''$ at 1–0 and 13$''$ at 2–1, requiring careful pointing relative to nearby quasars. At the distance of these galaxies, the beam covers typically < 3.5 kpc. In the centers of these "nearby" galaxies, 50 % of the nuclear CO concentrations are unresolved (< 7$''$) by the 30 m beams, so the apparent 2–1/1–0 ratios can be corrected to the same resolution with a point source approximation. For 11 of the 27 galaxies, the nuclear CO sources are "extended" (> 7$''$). and the line ratios were corrected with size estimates from cross scans, from comparisons with other telescopes with different beams and with interferometer maps, and, for a few galaxies, from maps made

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with the 30 m telescope. The resulting histogram of the CO 2–1/1–0 ratio peaks at a value of 0.6, as expected for clouds at $T_{\rm kin}$ 10 to 50 K, and n_{H_2} 200 to 600 $\rm cm^{-3}$. For a few of the galaxies, the ratio has been mapped as a function of radius from the nucleus, showing variations from 0.7 in the galaxies' centers to 0.4 in the outer parts.

III. THE DISTANT LUMINOUS SAMPLE

In this sample (Table 1), our detection rate is ~90%, and, for the galaxies which have been studied in more detail, the sizes of the CO emitting regions are mostly $< 7''$ (cf. Radford et al. 1990); interferometer data are needed for further information on the sizes of the CO concentrations. The results confirm the trend seen with the OVRO and NMA interferometers that the CO is centrally concentrated in highly IR-luminous galaxies.

A good illustration of what we're *not* seeing in this distant sample is the "nearby" (cz = 2800 km/s) galaxy NGC 3147. This galaxy has plenty of molecular gas; it has only 5% of the IR luminosity of Arp 220 but exactly the same CO luminosity. Figure 1 shows the CO emission mapped at the 30 m telescope superposed on an optical image. There is a striking absence of CO in the center of NGC 3147 — most of the CO is in a 10 kpc "ring", in sharp contrast to Arp 220, where the CO is concentrated in the inner 1 kpc. Even in NGC 3147 were 5 to 10 times more distant, in the redshift range of our "Deep" sample, we could still easily detect it, and partially resolve it, with the 30 m telescope.

As well as including galaxies with more centrally concentrated CO, our "Deep" sample contains the most CO–luminous galaxy found so far, namely 20087–0308, at cz = 32000 km/s, with $M_{\rm H_2} = 7\ 10^{10}\ \rm M_\odot$. It also contains galaxies in which we have made the farthest detections so far of CS and ^{13}CO (Arp 220; Solomon et al. 1990), $\rm HCO^+$ (Arp 220; Radford et al., in these proceedings), and HCN (Markarian 231; Solomon et al., in preparation). It also includes a tentative detection of CO in 15030+48, at cz = 65000 km/s, one of the most distant galaxies in which CO has been detected to date (June 1990).

For the "Deep" sample, the mean CO 2–1/1–0 ratio is 0.6 ± 0.2, as for the nearby sample. That is, there are no cases like M82, where the ratio is about 2, although the values for the "Deep" sample are obviously for entire galaxies, not just the central part, where the anomalous M82 ratio is observed. These low line ratios show that the CO is subthermally excited in regions of moderate $\rm H_2$ density, $\sim 350\ \rm cm^{-3}$. These ratios also indicate that the true CO(1–0) brightness temperatures are 6 to 13 K, even if the gas kinetic temperatures are much higher. Hence, even for these distant, IR–luminous galaxies, the $\rm M(H_2)/L_{CO}$ conversion factor appears to be similar to that measured for giant molecular clouds in our Galaxy.

Götz, M., 1990, Ph.D. Thesis, Universität Bonn.
Radford, S. J. E., Solomon, P. M., and Downes, D. 1990, Ap.J., submitted.
Solomon, P. M., Radford, S. J. E., and Downes, D. 1990, Ap.J., **348**, L53.

TABLE I. Distant, IR–Luminous Galaxies Detected in CO at the IRAM 30 m telescope.

Name	cz (km/s)	Δv (km/s)	I_CO (a)	log L_CO (b)	CO(2-1) / CO(1-0)
Mrk 1014	48944	180	1.7	9.9	
02483+4302	15420	184	5.7	9.4	0.7
03158+4227	40294	181	2.1	9.9	
03521+0028	45586	106	0.8	9.5	
04232+1436	23854	570	8.1	9.9	
VII Zw 31	16250	195	21.0	10.0	0.7
08030+5243	25035	465	6.3	9.9	
09320+6134	11811	502	15.6	9.6	0.4
10035+4852	19427	307	8.7	9.8	0.4
10190+1322	22953	385	7.4	9.8	
10495+4424	27603	295	1.5	9.3	
10565+2448	12928	197	21.8	9.8	0.6
Mrk 231	12650	225	22.0	9.8	0.7
Mrk 273	11324	365	15.6	9.5	
15030+4835	64950	400	1.2	10.1	
Arp 220	5450	480	109	9.7	0.5
17208-0014	12836	315	14.4	9.6	
19458+0944	29969	341	6.5	10.1	
20087-0308	31668	532	7.7	10.2	

(a) CO(1-0) K km/s (b) CO(1-0) K km/s pc^2

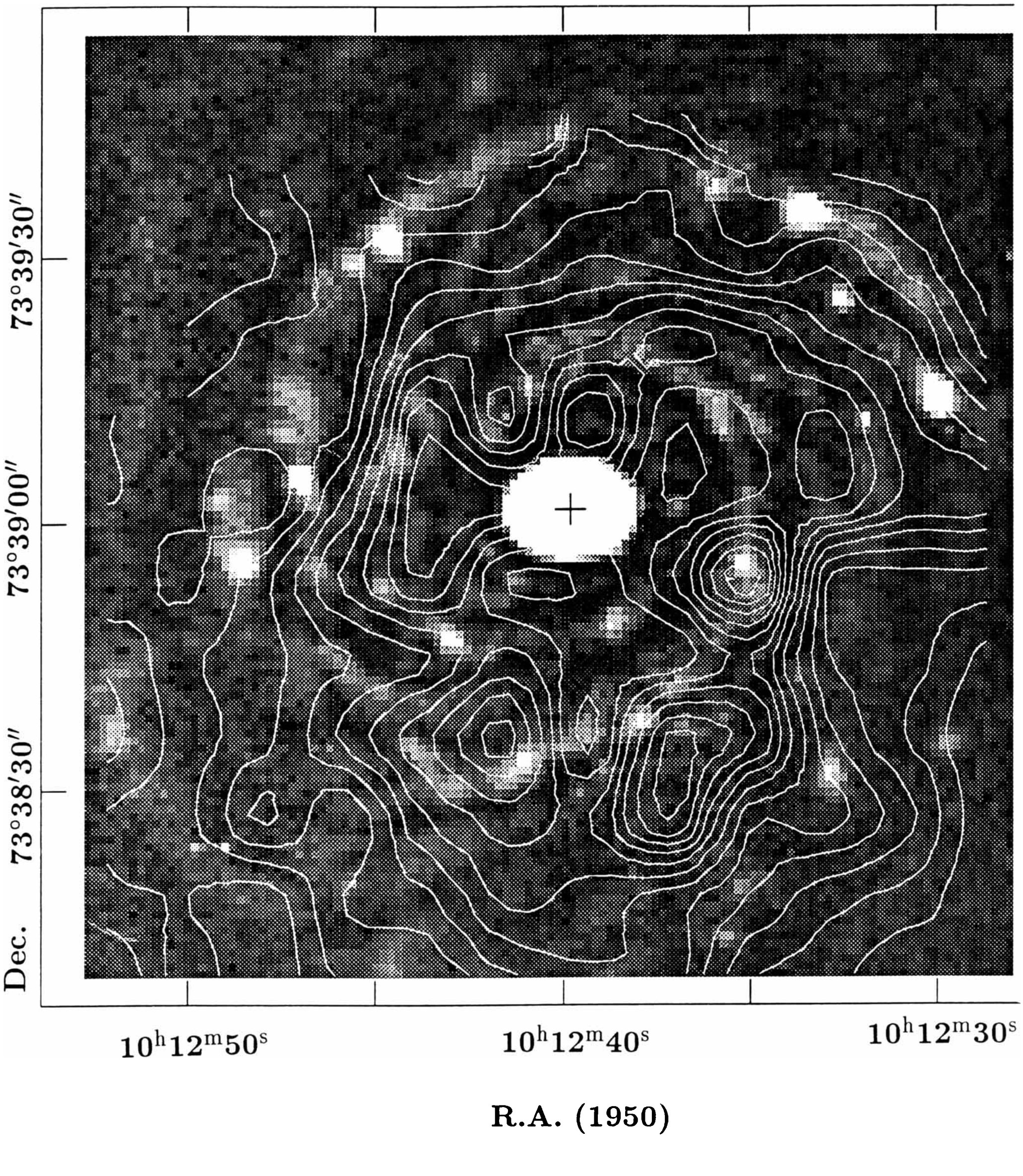

Fig. 1. CO emission from the galaxy NGC 3147, integrated over ± 300 $\mathrm{km\,s^{-1}}$ around the central velocity cz = 2800 $\mathrm{km\,s^{-1}}$; contour interval = 1 K $\mathrm{km\,s^{-1}}$, half-power beamwidth = 12.5″ The CO contours are superposed on an R–band CCD image made with the 1.2 m telescope of the Observatoire de Haute Provence by M. Dennefeld, with low spatial frequencies filtered out to better show the inner spiral arms. (Diagram prepared by F. Viallefond).