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CARBON MONOXIDE IN THE MAGELLANIC CLOUDS[1]

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ABSTRACT

We have detected ^{12}CO (2–1) emission at 11 of 22 positions in the LMC and, for the first time, at 6 of 16 positions in the SMC. All but one of the presently known Magellanic Cloud masers are associated with CO clouds; CO emission was also detected in the direction of several dark clouds and bright H II regions. In the LMC, the region south of 30 Doradus appears to be richest in CO, while in the SMC most detections are in the southwestern part of the Bar. CO emission from Magellanic Cloud objects tends to be weaker than that from Galactic objects; in addition, it is less widespread in the SMC than in either the Galaxy or the LMC.

We suggest that the combination of relatively low C and O abundances, relatively low gas-to-dust ratios, and relatively strong mean UV radiation fields in the Magellanic Clouds is the principal cause of these differences. In turn, this implies that use of the Galactic CO to H_2 ratio significantly underestimates the H_2 content of the Clouds. Such a result is consistent with models of stochastic star formation; consequently, low CO intensities may be a general property of low-mass galaxies in an active star-bursting phase, as is suggested by observations.

Subject headings: galaxies: Magellanic Clouds — interstellar: molecules — masers — stars: formation

I. INTRODUCTION

Molecular clouds consisting primarily of molecular hydrogen play a key role in the Galaxy. Between $R = 2$ and 10 kpc, the H_2 mass is roughly equal to the H I mass, making it a major constituent of the Galactic interstellar medium. At the same time, the formation of at least the massive stars takes place almost exclusively in giant molecular clouds, characterized by sizes of more than 20 pc and masses in excess of 10^5 $M_\odot$ (see Habing and Israel 1979; Myers *et al.* 1986). It is generally estimated that the Galaxy contains several thousands of such GMCs (e.g., Sanders 1981; Dame 1983).

As molecular hydrogen only has a quadrupole moment, it does not have emission lines at convenient visual or radio wavelengths. Limited observational possibilities exist (see, e.g., Shull and Beckwith 1982) in the ultraviolet (but only for relatively unreddened and tenuous clouds) and in the near-infrared (but only for relatively small zones of hot, excited hydrogen). For this reason, molecular cloud properties are usually derived from observations of the most abundant tracer molecule CO and its isotopes, under the assumption that the relation between CO and H_2 is known (see, e.g., Evans 1980). General similarity to Galactic results is found in CO observations of late-type spiral galaxy disks (Morris and Rickard 1982; Scoville 1983), but CO emission from dwarf irregular galaxies tends to be much weaker (Elmegreen, Elmegreen, and Morris 1980).

The latter authors discussed at some length possible causes of the difference between late-type spirals and dwarf irregulars but were unable to resolve the question, mainly because of the very complicated nature of CO formation and excitation and because of the lack of precise knowledge of the physical conditions in extragalactic molecular clouds. Yet it is a matter of importance to pursue this question not only in view of gaining insight into the general problem of molecule formation and destruction, but in particular in view of the crucial role played by molecular clouds in star formation processes and hence in theories of galactic evolution.

The Magellanic Clouds offer by far the best opportunity for such studies. By virtue of their close proximity to the Galaxy ($D = 53$ kpc and 63 kpc respectively; Humphreys 1984), a vast body of knowledge on the stellar and interstellar components of the Clouds has already been accumulated. For the same reason, observation of individual molecular cloud complexes is possible with relatively high linear resolution (typically 35 pc). A review of our current knowledge of dust and molecules in the Magellanic Clouds is given by Israel (1984). In this paper, we expand the existing sample of CO detections in the LMC (Huggins *et al.* 1975; Israel *et al.* 1982, hereafter Paper I) and add the first CO detections in the SMC. We confirm the generally low intensity levels of CO emission from the Clouds as compared to the Galaxy and show that the observed low dust-to-gas ratio, low metal abundances, and high UV emissivity of the Clouds may be a prime cause of the difference.

II. OBSERVATIONS

The new CO ($J = 2$–1) observations described in this paper were obtained in 1982 April using the Estec/Utrecht heterodyne submillimeter receiver and the ESO 3.6 m telescope at La Silla, Chile. The observational set up and calibration were the

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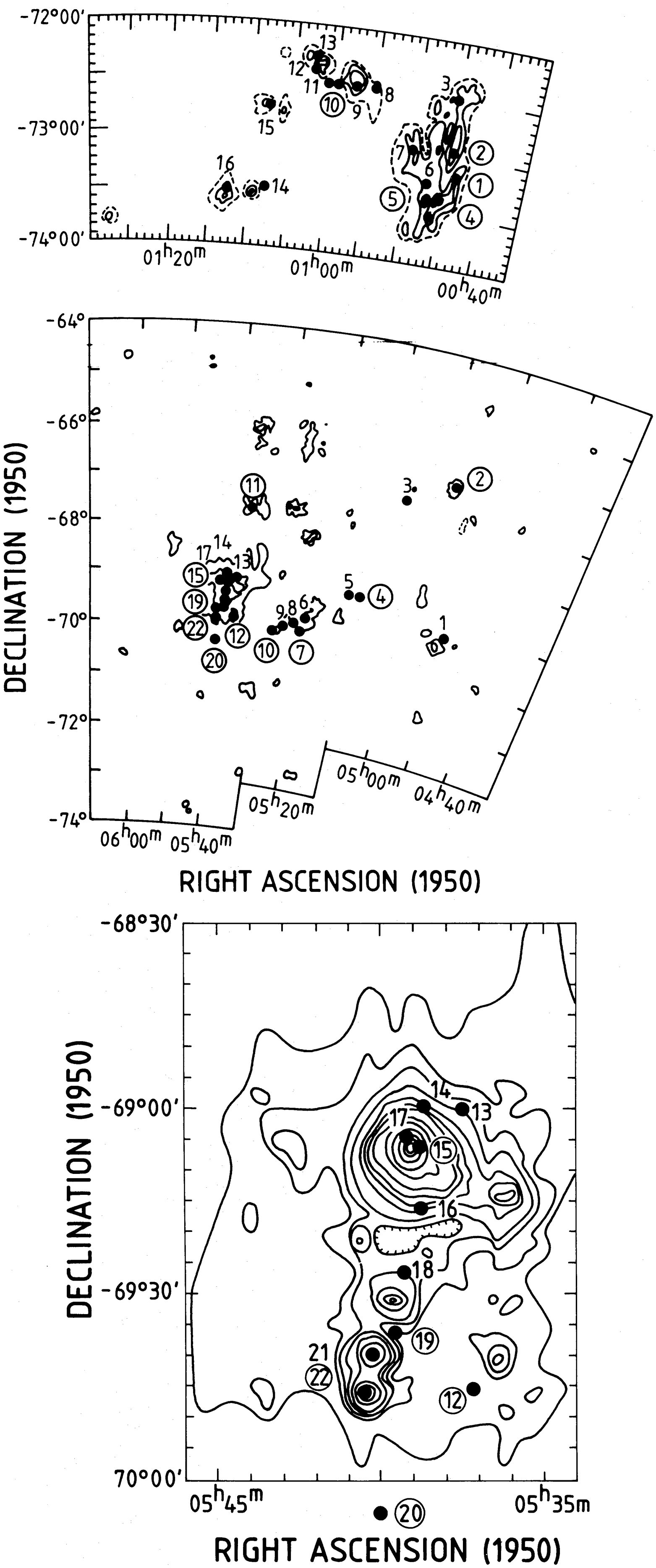

FIG. 1.—(*top*) Observed CO positions in the SMC marked on the 5 GHz radio continuum map by McGee, Newton, and Butler (1976). Numbers refer to Table 2. Circled numbers indicate CO detections. (*middle*) Observed CO positions in the LMC marked on the 5 GHz radio continuum map by McGee, Brooks, and Batchelor (1972). Numbers refer to Table 1. Circled numbers indicate CO detection. (*bottom*) Observed CO position in the LMC 30 Doradus region. In this figure, the size of the dots corresponds to the observing beam size. Otherwise as in top panel.

same as described in Paper I. We measured a beamsize of 2'.0 (HPBW); the overall system temperature was about T_{sys}(double sideband) = 2500 K; typical integration time on-source was 2000 s, and all observations were made in a position-switching mode. Weak standing wave patterns caused some problems; due to this, and to some variation in system performance during the observing run, the LMC data are of somewhat better quality than the SMC data. In the following, intensities are expressed in units of T_R^*, with $\eta_s = 0.5$ (Kutner and Ulich 1981). Because of the weakness of the Magellanic Cloud CO emission, we present only data obtained in the low-resolution filter bank (1 MHz, corresponding to 1.3 km s^{-1} at the observing frequency of 230 GHz).

In Figure 1 we have marked on radio continuum maps by McGee, Brooks, and Batchelor (1972) and McGee, Newton, and Butler (1976) all positions observed thus far (including those of Paper I). The new results are given in Tables 1 and 2; Figure 2 shows a selection of spectra. For convenience we have also included those obtained earlier (Paper I). Source selection was as follows. We observed all six known maser positions in the Magellanic Clouds (Caswell and Haynes 1981; Haynes and Caswell 1981; Scalise and Braz 1982; Whiteoak *et al.* 1983), the H II regions with the highest emission measures (Israel 1980), and several dark clouds (Hodge 1972, 1974). In addition, we observed several positions around the unusually bright LMC H II region complex 30 Doradus, the bright SMC H II regions N66 and N76, and the bright and compact SMC H II region N81 where near-IR molecular hydrogen emission was also detected (Koornneef and Israel 1985). Finally, we added some positions considered to be representative of the LMC and SMC main bars (LMC Nos. 5, 6, 8, 9, and 10; SMC Nos. 6, 7, and 8). There is some overlap between these samples: for instance, the masers are all accompanied by bright H II regions; LMC Nos. 14 and 22 and SMC Nos 4, 5, and 16 contain both dark clouds and H II regions within the beam, and two of the "representative" positions (neither of which, incidentally, yielded a detection) were near but not coincident with H II regions (LMC No. 9, SMC No. 7).

As a check on the consistency of the new results with those obtained earlier, we reobserved the strongest LMC CO cloud near N159; the results were the same to ~15%. Because the detected lines are resolved, detection quality is usually a factor of 2 or more better than indicated by the signal-to-noise ratio of peak T_R^*. Some of the data in Tables 1 and 2 are in parentheses and marked uncertain; this is due to possible confusion of a signal with baseline irregularities and applies mainly to SMC observations.

III. RESULTS

a) Individual Detections

In the LMC Bar, we detected CO at three of seven positions, including the H II region/maser source N105 (perhaps several clouds in the same line of sight, Fig. 2). The other two detections are the dark cloud H23 and a position (No. 10) not associated with a cataloged H II region or dark cloud. Outside

TABLE 1

^{12}CO (2–1) OBSERVATIONS IN THE LMC[a]

Number	Object[b]	α(1950)	δ(1950)	Peak T_R^* (K)	ΔV (km s^{-1})	V_{LSR} (km s^{-1})	H I Cloud[c]	V_{LSR} (km s^{-1})	Remarks[d]
1.........	N77BC	04h50m06s	−69°16'.5	<1.1	...	...	L34	...	H II
2.........	N11	04 56 42	−66 28.4	0.5 ± 0.3	9	+286	L2	278 ± 12	H II
3.........	N20	05 05 12	−66 57.5	<0.5	...	...	L27	...	H II
4.........	N105	05 10 13	−68 57.1	1.4 ± 0.3	16[e]	+238	L39	239 ± 10	H II + M
				0.9 ± 0.3	5	+312	...	...	
5.........	...	05 11 55	−68 57.1	<1.2	...	...	L4?	...	
6.........	...	05 21 00	−69 35.0	<0.8	...	...	...	...	
7.........	H23	05 22 00	−69 48.0	0.9 ± 0.3	7	+258	L28	247 ± 21	DC
8.........	...	05 23 00	−69 40.0	<0.8	...	...	...	...	
9.........	...	05 25 00	−69 45.0	<0.9	...	...	...	...	
10.........	...	05 27 00	−69 50.0	1.0 ± 0.3	7	+229	...	...	
11.........	N59	05 35 30	−67 36.0	0.8 ± 0.25	7	+267	L14	290 ± 12	H II
12.........	H47	05 37 00	−69 45.0	0.7 ± 0.25	5	+258	...	254 ± 17	DC
13.........	30 Dor	05 37 30	−69 00.0	(0.9 ± 0.4	4	+227)	L48	241 ± 17	DC; uncertain
14.........	H51	05 38 45	−68 59.5	<1.6	...	...	...	...	DC; PI
15.........	30 Dor	05 38 50	−69 07.0	0.8 ± 0.3	7	+245	L32	236 ± 16	H II; PI
16.........	30 Dor	05 38 50	−69 17.0	<0.9	...	...	L32	...	H II; PI
17.........	30 Dor	05 39 10	−69 05.0	<0.6	...	...	L32	...	H II; PI
18.........	N158C	05 39 10	−69 27.0	<0.9	...	...	L32	...	H II; PI
19.........	N160A	05 39 30	−69 37.0	1.1 ± 0.3	7	+240	L48	241 ± 17	H II; PI
				1.0 ± 0.3	6	+304	...	...	
20.........	H53/54[f]	05 40 00	−70 10.0	1.0 ± 0.25	6	+237	L49	239 ± 16	DC
21.........	N160A	05 40 12	−69 39.7	<1.2	...	...	L48	...	H II + M
22.........	N159/H57[g]	05 40 30	−69 46.0	2.6 ± 0.2	7	+235	L48	241 ± 17	H II + M + DC; PI
				1.0 ± 0.3	8	+292	...	...	

[a] $V_{Hel} = V_{LSR} + 16$ km s^{-1}.

[b] N, Henize 1956; H, Hodge 1972.

[c] L, H I cloud number assigned by McGee and Milton 1966.

[d] H II, on or near H II region; M, OH or H_2O maser present (Caswell and Haynes 1981; Haynes and Caswell 1981; Scalise and Braz 1982; Whiteoak *et al.* 1983); DC, dark cloud; PI, discussed in Paper I.

[e] Possibly a blend of two clouds in the line of sight.

[f] In reference position of No. 12.

[g] Combination of new result and Paper I.

TABLE 2

^{12}CO (2–1) OBSERVATIONS IN THE SMC[a]

Number	Object[b]	α(1950)	δ(1950)	Peak T_R^* (K)	ΔV	V_{LSR}(CO) (km s^{-1})	V_{LSR}(H I) (km s^{-1})	Remarks[c]
1.........	...	00^{h}44^{m}00^s	−73°15′.0	1.3 ± 0.4	6	+112	+110	H II?
				(1.3 ± 0.4	4	+185)	+160	Uncertain
2.........	S7	00 44 48	−72 57.0	1.2 ± 0.4	18[d]	+118	+125	H II + M
				1.3 ± 0.4	9	+170	+160	
3.........	S8	00 45 00	−72 30.0	(1.3 ± 0.5	10	+116)	+120	H II?
4.........	N19/S9/H10	00 45 42	−73 24.7	2.3 ± 0.4	7	+123	+125	H II + M + DC
5.........	N30/S13/H17	00 47 12	−73 24.0	1.0 ± 0.35	6	+90	+115	H II + DC
6.........	...	00 47 30	−73 15.0	<1.5	...	...	...	
7.........	H26	00 50 00	−73 00.0	<1.5	...	...	...	DC
8.........	...	00 55 00	−72 30.0	(0.6 ± 0.3	9	+129)	+120	Uncertain
				(1.1 ± 0.4	5	+163)	+163	Uncertain
9.........	N66/S17	00 57 30	−72 30.0	<0.7	...	...	...	H II; Paper I
10.........	N66/S17	01 00 00	−72 30.0	0.7 ± 0.3	12	+110	+117	H II
11.........	...	01 01 00	−72 30.0	<1.0	...	...	...	Paper I
12.........	N76/S20	01 02 30	−72 22.5	<0.6	...	...	...	H II
13.........	N76/S19/21	01 02 30	−72 15.0	<0.9	...	...	...	H II
14.........	N81	01 07 48	−73 28.0	0.7 ± 0.3	5	+135	+150	H II
15.........	S24	01 08 00	−72 44.0	(1.3 ± 0.5	5	+130)	+125	H II; uncertain
16.........	N83/S26/H45	01 12 30	−73 30.0	<0.6	...	...	...	H II + DC

[a] $V_{Hel} = V_{LSR} + 11$ km s^{-1}.
[b] S, McGee *et al.* 1976; N, Henize 1956; H, Hodge 1974. H II, on or near H II region; M, H_2O maser present; DC, dark cloud.
[d] Possibly a blend of two clouds in the line of sight.

the Bar, we detected weak CO from the high emission measure H II regions N11 and N59, but not from N77BC and N20. We also detected, near an H_2O maser, weak CO emission at one position in 30 Doradus itself (cf. Paper I) and perhaps from a dark lane just north of 30 Doradus (No. 13). The remaining four (and stronger) detections are all to the south of 30 Doradus itself; they include the bright H II region/maser source N159 (Paper I). At the position of the H II region/maser source N160A, no CO was detected; a positive detection was, however, made at a position 4′.8 to the northwest (No. 19). These detections correlate well with the concentration of dark clouds in the vicinity of 30 Doradus and in particular to the south of it (Hodge 1972; van den Bergh 1974); likewise, the results by Cohen, Montani, and Rubio (1984) confirm the presence of a major CO concentration south of 30 Doradus.

In the SMC southwest Bar we detected CO at four positions, including the two H II region/maser sources S7 and N19/S9, the H II region N30/S13, and a position (No. 1) coinciding with an unlisted peak in the radio continuum map of McGee, Newton, and Butler (1976). We observed six positions on or near the large H II region complexes N66/S20 and N76/S19, 21 but detected only a weak CO signal at one position (No. 10) just east of N66. CO was weakly detected in the direction of N81 (cf. Koornneef and Israel 1985). Again the predominance of CO in the southwest Bar correlates well with the concentration of dark clouds in this part of the SMC (Hodge 1974; van den Bergh 1974; see also Israel 1984).

We have compared CO line velocities with H I line velocities at the same positions (McGee and Milton 1966; Bajaja and Loiseau 1982; see Tables 1 and 2). Detected CO lines generally fall within 15 km s^{-1} of an H I peak velocity, and even in the case of the extreme velocities seen at LMC Nos. 4, 19, and 22 and SMC Nos. 1 and 2 the velocities fall within the range covered by H I (cf. Paper I). We confirm the trend noted in Paper I: most detected lines are quite weak, typically about $T_R^* = 1.0$–1.5 K. In the LMC, the H II region/maser source N159 is still the strongest source by almost a factor of 2. In the SMC, the H II region/maser source N19 shows a similar strength. Somewhat weaker CO emission is associated with three of the four remaining maser positions; these positions tend to yield the strongest CO detections. In Table 3 we summarize the CO results as a function of the type of object observed. Because of overlap, the sum of the subsamples may be larger than the total listed. Not surprisingly, the highest detection rate after the maser sources is that of the dark clouds, followed by the H II regions.

TABLE 3

CO DETECTION STATISTICS AS A FUNCTION OF TYPE OF OBJECT

	NUMBER OF POSITIONS						PERCENTAGE DETECTED[a]	
	LMC			SMC				
OBJECT	Observed	Detected	Uncertain	Observed	Detected	Uncertain	LMC	SMC
H II regions	13	6	1	12	5	2	50	40(50)
Masers	4	3	...	2	2	...	75	100
Dark clouds	5	4	...	4	2	...	80	50
Other	4	1	...	4	1	1	25	25(38)
Total[b]	22	10	1	16	6	3	47	31(40)

[a] Values in parentheses assume that half the uncertain detections are real.
[b] Because of overlap between subsamples, totals do not equal the sum of individual samples.

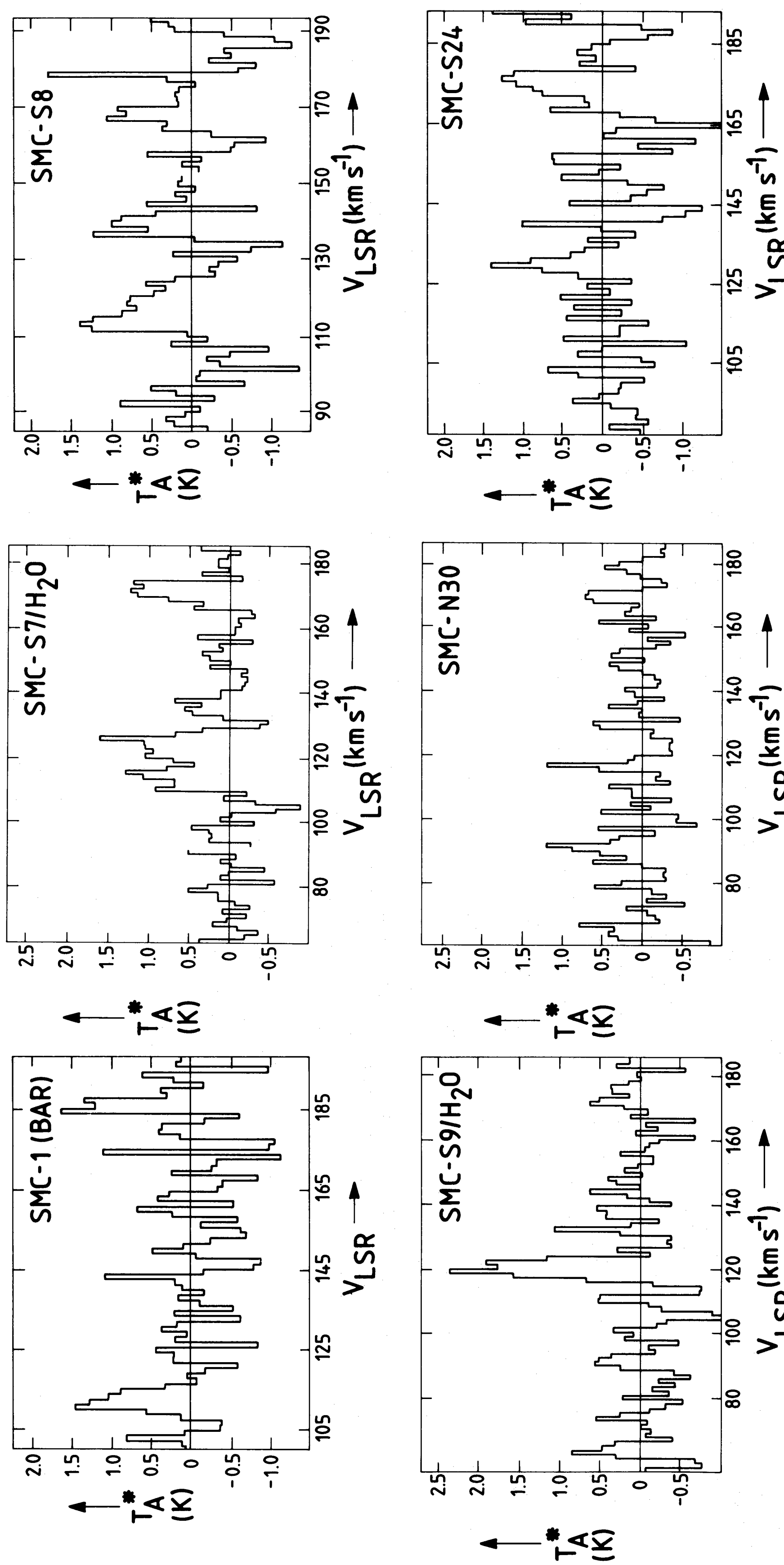

FIG. 2.—Selection of observed CO (2–1) spectra in LMC and SMC

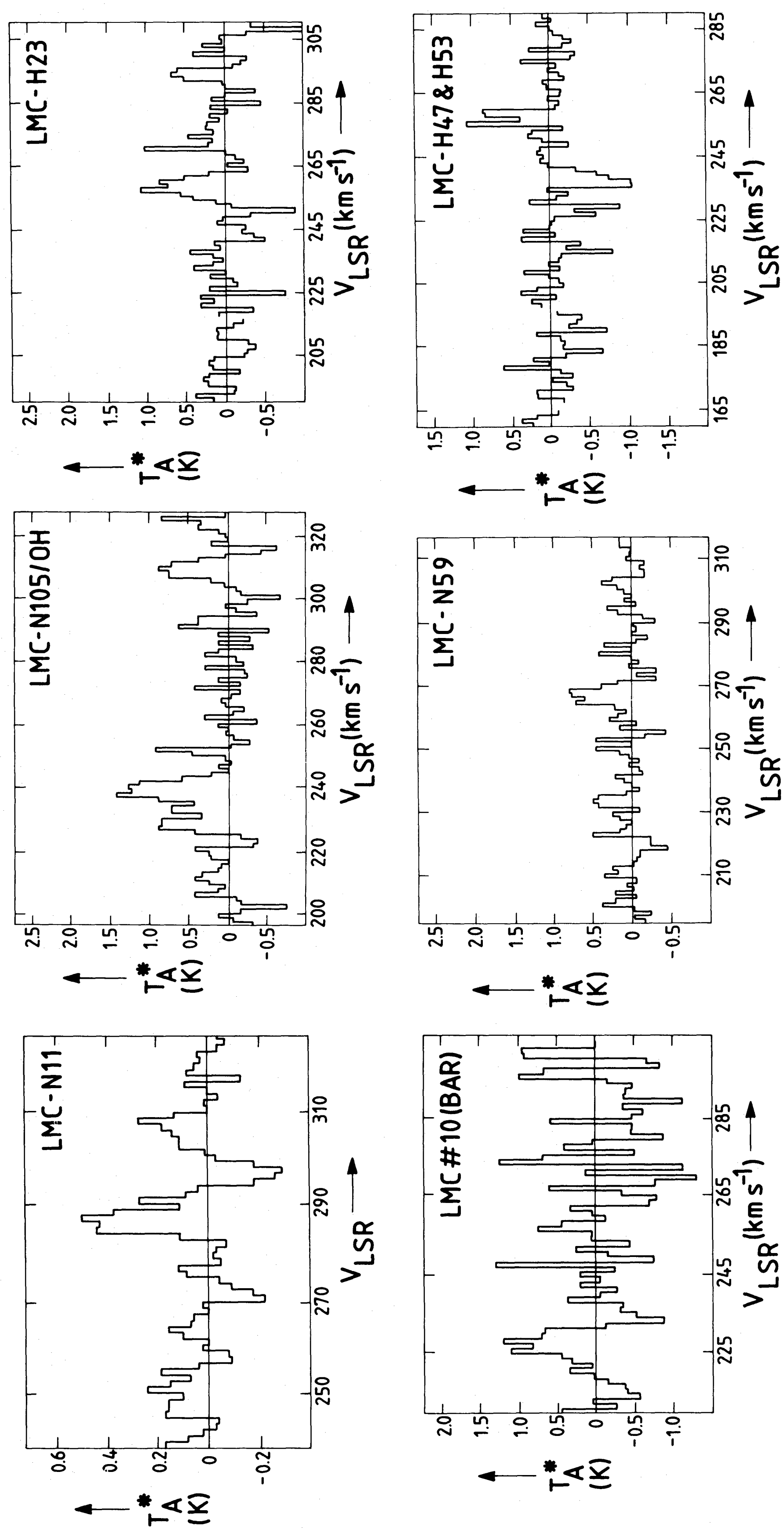

FIG. 2.—*Continued*

Overall, the detection rate of the observed H II regions is ~50%; it is remarkable that several high emission measure H II regions yielded negative results (LMC: N77BC, N20, most of 30 Dor, N158C; SMC: most of N66, N76). The positions chosen as representative (not preselected for the presence of masers, H II regions, or dark clouds) yielded poor detection rates.

b) Weakness of CO *Emission*

A striking result is the *weakness* of the ^{12}CO emission from the Magellanic Clouds, as shown in Tables 1 and 2. Our results for the CO (2–1) emission are confirmed by CO (1–0) observations made with a similar beam (Gardner 1984), and, more generally, in both the SMC and the LMC by the extensive CO (1–0) survey with the Columbia 8′ beam (Cohen, Montani, and Rubio 1984; Rubio, Montani, and Cohen 1984).

Elmegreen, Elmegreen, and Morris (1980, hereafter EEM) have shown that the area-integrated brightness $\int T_b dS$ is a useful tool for comparing the CO emission in the Galaxy with that in other galaxies in a quantitative way. Strictly speaking, one should consider the area-integrated, velocity-integrated brightness $\int T_b dSdv$. However, both the sample of Galactic giant molecular clouds used by EEM and the CO clouds detected by us in the LMC and the SMC have mean velocity widths of 7–8 km s^{-1}, whereas velocity gradients in Galactic samples are of order 3–4 km s^{-1} or less. For the sake of consistency with the discussion by EEM, we will in the following use $\int T_b dS$. For clouds smaller than the beam, this quantity is *independent* of the beam filling factor; for clouds larger than the beam it underestimates the cloud area-integrated brightness by the fraction of cloud outside the beam. For the sample of Galactic GMCs, the mean area-integrated brightness is $\int T_b dS = (1.3 \pm 0.4) \times 10^4$ K pc^2 (EEM); the mean dimensions are of order 20 × 100 pc, corresponding to a mean surface area $\int dS = (2.1 \pm 0.3) \times 10^3$ pc^2 (Blitz 1978; Stark and Blitz 1978). Moreover, virtually all CO in the Galaxy is found in such giant complexes (Sanders 1981; Dame 1983). Thus, taking into account our beam size of 0.8–1.0 × 10^3 pc^2, a Galactic giant molecular cloud complex would show up in the Magellanic Clouds with a temperature of about 4 K and an area-integrated brightness of about 4.5×10^3 K pc^2 as long as the beam is more or less centered on the complex.

The mean level of *detected* CO emission in the Magellanic Clouds falls far short of these values by a factor of over 4; even the brightest detections in both LMC and SMC have only about half this strength. This result could be explained in the following ways: (*a*) Magellanic molecular cloud complexes have the same dimensions as those in the Galaxy, but are intrinsically less bright in CO; (*b*) Magellanic molecular cloud complexes have CO brightness temperatures similar to those in the Galaxy, but systematically smaller dimensions; or (*c*) we have systematically pointed off the observed Magellanic molecular cloud complexes.

We consider possibility (*c*) the least likely, because of the number of positions sampled, the relative linear sizes of our beam and of Galactic GMCs, and our observing strategy (pointing at maser positions, H II regions, and dark clouds)—cf. also the LMC results by Cohen, Montani, and Rubio (1984). We also consider possibility (*b*) to be an unlikely solution. An estimate of Magellanic GMC sizes may be obtained from the dark cloud observations by Hodge (1972, 1974). Although probably incomplete, they show the existence of 68 cloud complexes in the LMC (with a mean surface area per cloud complex $\int dS = 3.3 \times 10^3$ pc^2) and 45 cloud complexes in the SMC (with a mean surface area per cloud $\int dS = 1.2 \times 10^3$ pc^2). These dimensions are comparable to those of Galactic GMCs (see also Israel 1984). We are thus left with possibility (*a*): most likely, the CO complexes detected in the Magellanic Clouds have brightness temperatures lower than Galactic GMCs by at least a factor of 2 and possibly a factor of 4. Moreover, these results are dominated by the relatively strong detections obtained in the LMC Greater Doradus region and the SMC southwest Bar region. The five detections in the Greater Doradus region contribute 60% of the total observed signal; likewise, the four detections in the SMC southwest Bar contribute over 70% of the total observed signal. We conclude that the LMC Greater Doradus region and the SMC southwest Bar are regions relatively rich in molecular clouds but nevertheless show CO emission significantly weaker than would be expected from Galactic GMCs at Magellanic distances. Moreover, the rest of the SMC Bar and probably also the SMC Wing have a low CO content; the few clouds detected show weak CO signals, even with respect to the clouds in the "active" region. We again note that the above results are confirmed by the CO (1–0) observations carried out by Cohen, Montani, and Rubio (1984) and Rubio, Montani, and Cohen (1984) with the larger Columbia beam and are in agreement with results obtained for other Magellanic dwarf irregulars by EEM.

IV. DISCUSSION

a) Explanations for the Weakness of CO *Emission in Magellanic-Type Galaxies*

All present observations thus indicate low intrinsic CO intensities in the Magellanic Clouds, and especially so in the SMC. The same conclusion was drawn for other irregular dwarf galaxies (EEM). As shown by these authors, several explanations are possible. First, CO may be underabundant with respect to hydrogen, especially in view of the generally low metal abundances of dwarf galaxies. Second, the rate and efficiency of massive star formation may be high in dwarf galaxies, resulting in rapid destruction of molecular cloud complexes and in cloud lifetimes shorter than usual in our Galaxy. Third, the low-energy cosmic ray intensity may be less in dwarf galaxies than in our Galaxy, resulting in lower cosmic-ray heating rates, hence in lower CO excitation temperatures.

We believe the last explanation to be the least likely, for the following reasons. For low CO excitation temperatures ($T_{ex} \lesssim 10$ K), the CO (2–1) brightness temperature should be appreciably less than the CO (1–0) brightness temperature in the same beam. This is contrary to what is observed (cf. Gardner 1984). Moreover, a fair number of supernova remnants have been identified in both LMC and SMC (Mathewson *et al.* 1983) and doubtless there are more to be found. Statistics of supernova remnants by Mathewson *et al.* (1983) and Tammann (1982) show that the present supernova rate per unit total mass is *higher* in the Magellanic Clouds than in the Galaxy by a factor of 2–3, yet the cosmic-ray flux would have to be *lower* by a factor of 10 to explain the CO results (cf. Goldsmith and Langer 1978; EEM). There are in addition some indications that the mean cosmic-ray flux in the LMC is indeed of the same order of magnitude as that in the Galaxy (Houston, Riley, and Wolfendale 1983). The second explanation is more likely. In fact, we believe that it explains the lack of CO near the giant H II region complex 30 Doradus itself (cf.

Paper I), as well as the lack of CO in the direction of giant H II regions in several other dwarf galaxies noted by EEM and perhaps also near SMC-N66 and N76. By its nature this explanation involves, however, only a local effect; it is incapable of explaining weak or absent CO emission in those parts of the Magellanic Clouds that are not adjacent to large and bright H II regions, i.e., most of the Clouds.

With respect to the first explanation, it is known that in the Magellanic Clouds heavy elements, including carbon, oxygen, and nitrogen are underabundant relative to the solar neighborhood, e.g., Orion A (see Dufour 1984). This strongly suggests that CO will also be underabundant. However, an underabundance of CO, unless very severe, is unlikely to influence ^{12}CO intensities signficantly, because the ^{12}CO transitions are optically thick at low J levels for column densities $N(^{12}\mathrm{CO}) > 10^{15}$ cm^{-2} (see, e.g., Knapp *et al.* 1982). However, the dust-to-(atomic) gas ratio in the LMC and in particular the SMC is also much lower than in the Galaxy (Koornneef 1982, 1984; Lequeux *et al.* 1984), and several authors have remarked on the low extinction levels in both LMC and SMC. Finally, an extrapolation of observed UV flux densities (Morgan and Nandy 1978; Morgan, Nandy and Carnochan 1979) to $\lambda = 1000$ Å yields peak UV energy densities in selected LMC and SMC regions about an order of magnitude higher than the mean Galactic value of $U = 0.35 \times 10^{-16}$ ergs Å^{-1} cm^{-3} (Habing 1968). As CO is dissociated by UV radiation shortward of 1120 Å, we believe that in particular the combined effect of a low dust-to-gas ratio and a strong interstellar UV radiation field is the key to understanding the weakness or absence of ^{12}CO in the Magellanic Clouds by providing less shielding and higher destruction rates of CO molecules.

Detailed model calculations taking into account interstellar chemistry and radiative transfer effects are needed to gauge the effects of variations in metal and dust abundances in different UV radiation field environments. To illustrate the potential importance of these effects, we have constructed some simple idealized models, described below.

b) A Simple Model for CO *Depletion in Magellanic-Type Galaxies*

In the Galaxy, some 75%–85% of all molecular hydrogen is estimated to be concentrated in giant molecular cloud complexes in the mass interval $M = 10^5$–10^7 $M_\odot$ with a mean around $M = 1.5 \times 10^6$ $M_\odot$ (Sanders 1981; Dame 1983). As Magellanic dark cloud complexes have dimensions similar to those of Galactic molecular cloud complexes (§ III*b*), we assume their masses to be similar as well, so that our model molecular cloud will have a mass $M = 1.5 \times 10^6$ $M_\odot$. Observations of Galactic molecular cloud complexes, furthermore, show them to be strongly clumped and to consist of several well-defined dense, parsec-sized clumps (see, e.g., Blitz and Shu 1980; Thaddeus 1982; Bally and Israel 1986). Several authors have determined the mass and size distributions of Galactic molecular cloud complexes in the form $N(M) \propto M^{-n}$ or $N(d) \propto d^{-m}$. Values for n range from $+0.5$ to $+1.8$ and values for m from -0.5 to $+1.8$ (for references, see Drapatz and Zinnecker 1984; Israel 1985). The assumption that the distribution of clumps within a complex is similar to the distribution of complexes themselves appears to be borne out by an analysis of clumping in the (Galactic) S255 molecular cloud complex, where the value $n = 1.0 \pm 0.2$ is found with clump masses ranging from 10^2 to 10^4 $M_\odot$ (Bally and Israel 1986). For simplicity's sake we will in the following assume that all clumps are spherical and homogeneous.

In a Galactic molecular clump, CO dissociating photons penetrate to a typical depth d_0 corresponding to $A_V = 1.5$ mag, after which shielding by dust particles largely protects CO from the damaging influence of the UV radiation field. By assuming that all CO is dissociated up to d_0, and none beyond, only a small error is made (see Dalgarno, De Jong, and Boland 1980). Using the relation between total hydrogen column density and A_V as given by Jenkins and Savage (1974), we find $d_0 = 2.4 \times 10^2 n(\mathrm{H})^{-1}$, where n(H) is the total hydrogen space density in cm^{-3}.

The effect of the different physical conditions in, e.g., the Magellanic Clouds can be taken into account by multiplying the expression for d_0 by a factor f_{UV} which represents the (in this case) greater penetrating power of the ambient UV radiation field. This factor f_{UV} is a function, normalized to Galactic conditions, of the ambient UV radiation field intensity, UV extinction, and dust abundance: $f_{\mathrm{UV}} = U'_{\mathrm{UV}} f_A f_d$. Here, U'_{UV} is the UV energy density at $\lambda = 1000$ Å as compared to the mean Galactic value; f_A is defined as $3.6 A_V / A_{1000}$ (i.e., $A_{\mathrm{UV}} = 5.4$ corresponds to $A_V = 1.5 f_A$), so that for the Galaxy f_A is unity, and f_d is the dust depletion factor with respect to the solar neighborhood as determined from dust-to-gas ratios.

Thus, as f_{UV} increases, dissociating radiation penetrates deeper into the clumps making up the molecular cloud complex, so that the CO cores of these clumps become both smaller and less massive. It is clear that the influence of an increase in f_{UV} will be greatest for the clumps with the lowest density. In the case of optically thin line emission, such as that of ^{13}CO, the corresponding decrease in signal strength is proportional to the decrease in CO core mass, whereas in the case of optically thick line emission, such as that of ^{12}CO, the decrease in signal strength is proportional to the decrease in CO core (projected) surface area. Hence, the signal of an optically thin transition is more affected by an increase in f_{UV} than the signal of an optically thick transition. Integration over the appropriate clump distribution yields the decrease in CO content and the decrease f_{CO} in CO signal strength of the whole complex. Because the ratio of surface area to volume is much higher for a strongly clumped molecular cloud complex than for a homogeneous molecular cloud, changes in f_{UV} affect the former much more strongly than the latter.

Two more aspects need to be taken into consideration. First, if the CO abundance A(CO) of a molecular cloud complex is different from that in a solar neighborhood cloud complex, this would hardly affect the emission in an optically thick transition (^{12}CO), but the emission in an optically thin transition (^{13}CO) would vary proportionally to the change in abundance. Second, it has been suggested that CO might be significantly self-shielding (Bally and Langer 1982). A detailed treatment of this possibility was given by Glassgold, Huggins, and Langer (1985). This possibility is important, because it is suggested that ^{12}CO may be self-shielding for $A_V > 1.0$ mag, making it the major factor determining $d_0(^{12}\mathrm{CO})$ and an important factor in determing $d_0(^{13}\mathrm{CO})$. Thus, for solar neighborhood ^{12}CO abundances, d_0 would be virtually independent of f_{UV}. It should be noted, however, that at present the actual photodissociation rates of CO are still very uncertain (E. F. van Dishoeck, private communication; see also Glassgold, Huggins, and Langer 1985). Moreover, if CO is underabundant by more than a factor of 1.5, then the effect of f_{UV} would again dominate up to the point where the depleted CO would have built up sufficient column density to self-shield again.

We have calculated expected decreases in ^{12}CO intensities,

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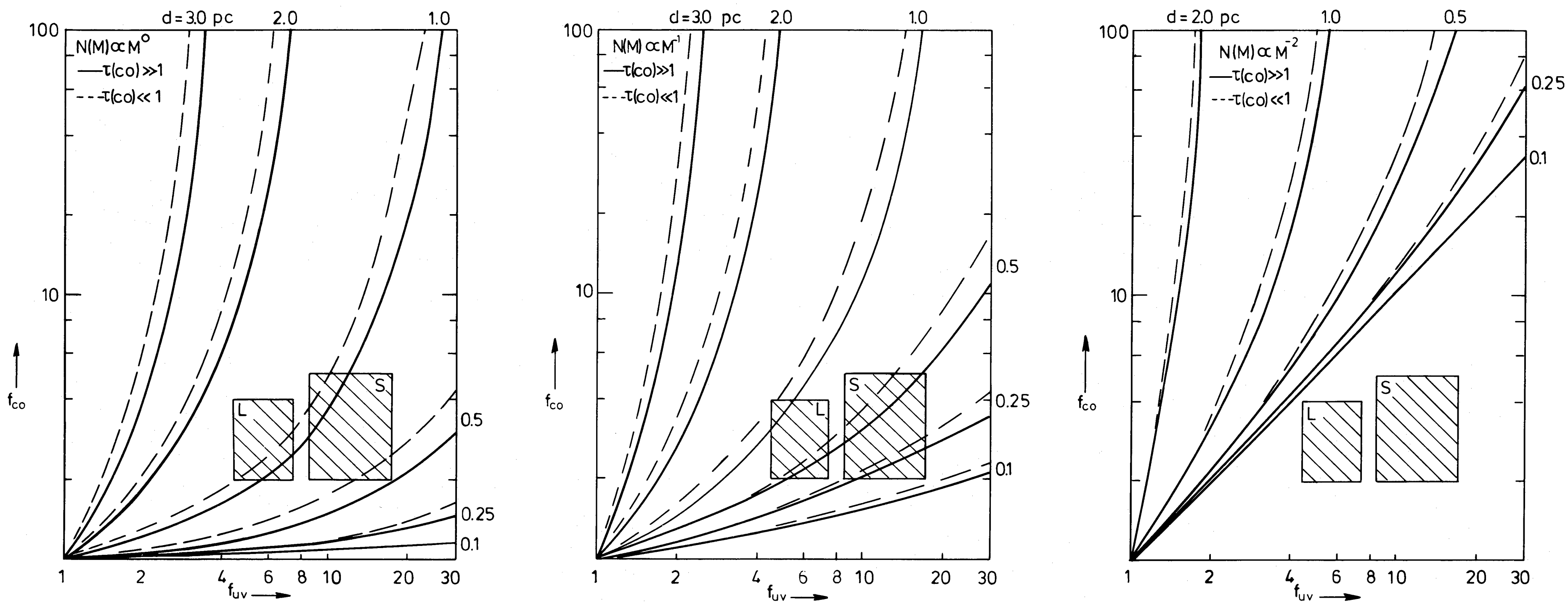

FIG. 3.—Decrease of ^{12}CO emissivity of a giant molecular cloud complex (f_{CO}) as a function of varying UV penetrating power f_{UV}. The shaded regions indicate the range of parameters applicable to the LMC and SMC. Case *a*; see §§ IV*b* and IV*c*.

$f(^{12}CO)$, for the moment ignoring the effects of abundances and self-shielding. All calculations were made for the model GMC with M(total) $= 1.5 \times 10^6\ M_\odot$, and for the following cases.

a) Constant clump diameter d pc, with clump mass M (hence also clump density) varying as $N(M) \propto M^{-n}$, for various values of d and for $n = 0$, $+1$, and $+2$, which cover the most likely values for n as deduced from Galactic observations. The results are shown in Figure 3; dashed lines indicate results for optically thin emission.

b) Constant clump density n(H) with clump diameter d (hence also clump mass) varying as $N(d) \propto d^{-2.5}$. This particular dependence of $N(d)$ was chosen because it corresponds to Sanders' (1981) analysis of Galactic observations. The results for several values of n(H) are shown in Figure 4*a*.

c) Constant clump mass M, again with $N(d) \propto d^{-2.5}$, in which clump diameter and clump density vary simultaneously. The results for several values of M are shown in Figure 4*b*.

The results indicate that modest increases of f_{UV} generally lead to significant increases of f_{CO}, hence to significant decreases in the expected CO signal strength. As noted before, optically thin emission is affected more strongly than optically thick emission. The results shown in Figures 3 and 4 should give a substantially correct impression of the decrease in CO signal strength model GMCs as a function of the (greater) penetrating power of UV radiation in cases where CO self-shielding is negligible, either because it is intrinsically unimportant or because it is offset by CO abundances significantly lower than in the solar neighborhood. In the latter case, the curves should retain their validity up to $f_{UV} \approx 0.7A$(CO), where A(CO) is the factor by which CO is underabundant. Beyond this value of f_{UV}, f_{CO}, would be more or less constant. At the same time, (dashed) curves for optically thin ^{13}CO should in addition be displaced upward by about a factor of A(CO). Thus, the total amount of CO may be quite small in galaxies with lower metal abundance, lower dust content, and higher UV energy density than the Galaxy, even for galaxies with relatively large total mass.

c) *Molecular Clouds in LMC and SMC*

As mentioned before, conditions in the Magellanic Clouds are reasonably well known due to their proximity to the Galaxy. Thus we can make a numerical estimate for f_{UV}. Extrapolation of the UV emission of nine selected LMC regions and one SMC (Bar) region observed by Morgan and Nandy (1978) and Morgan, Nandy, and Carnochan (1979) to $\lambda = 1000$ Å yields a UV energy density $U = 5 \times 10^{-16}$ ergs Å^{-1} cm^{-3} with a spread by a factor of 2; for a region in the SMC Wing, $U = 0.2 \times 10^{-16}$ ergs Å^{-1} cm^{-3}. The mean Galactic value is $U = 0.35 \times 10^{-16}$ ergs Å^{-1} cm^{-3} (Habing 1968). However, the authors remark that the observed UV fluxes are peak values. Thus, $U'_{UV} = 1$–10 for both LMC and SMC. Higher UV energy densities in the Magellanic Clouds are consistent with the higher rates of luminous star formation in the Magellanic Clouds. The luminous star formation rate per unit total mass is 2.7 for the LMC and 1.6 for the SMC, whereas the luminous star formation rates per unit *gas* mass are 1.5 and 0.3 respectively (Israel 1980; Lequeux 1984, and references therein). As the most probable values for U'_{UV}, we therefore adopt 1.5–2.5 for the LMC, and 0.75–1.5 for the SMC. The other factors making up f_{UV} can be determined with higher accuracy. The UV reddening laws presented by Rocca-Volmerange *et al.* (1981) and Lequeux *et al.* (1984) yield $f_A = 0.75$ for the LMC and $f_A = 0.62$ for the SMC at $\lambda = 1000$ Å. For the dust depletion we take $f_d = 4$ for the LMC and $f_d = 17$ for the SMC (Koornneef 1982, 1984; Lequeux *et al.* 1984). Thus, we find $f_{UV} = 4.5$–7.5 for the LMC, and $f_{UV} = 8.5$–17.5 for the SMC. In § III*b* we found f_{CO} to be of order 2–4 in the

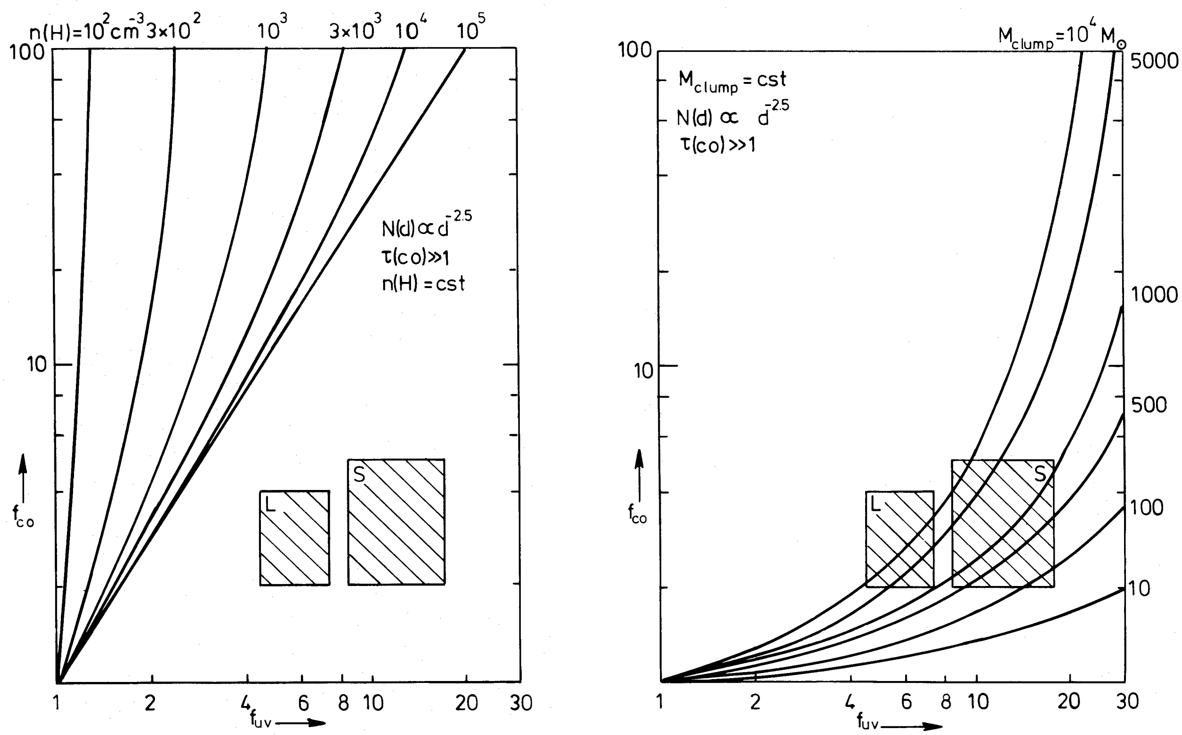

FIG. 4.—As Fig. 3, but for cases *b* and *c*; see §§ IV*b* and IV*c*

Magellanic Clouds. The corresponding parameter space is indicated in Figures 3 and 4, denoted by "L" for LMC and "S" for SMC.

It is clear that the weak CO signals observed in the Magellanic Clouds can generally be explained by the increase in f_{UV} suggested by observations. If no or little ^{12}CO self-shielding takes place, clump distributions of the form $N(M) \propto M^{-2}$ can be ruled out, as well as those of the form $N(d) \propto d^{-2.5}$ for constant n(H). In both cases the expected decrease in CO signal strength greatly exceeds the observed decrease. A clump distribution with $N(d) \propto d^{-2.5}$ with constant M would fit the SMC but lead to rather large clump masses for the LMC. The most realistic situation is given by $N(M) \propto M^{-1}$ (Fig. 3*b*) with clump sizes of order 0.25–1.0 pc. It is encouraging that these parameters are very close to those found in the S255 molecular cloud complex (Bally and Israel 1985). These results are, at least for ^{12}CO, largely independent of abundance variations. If ^{12}CO is indeed strongly self-shielding and Magellanic CO abundances were to be the same as in the Solar Neighborhood, none of the cases considered would fit the observations, since f_{UV} would essentially be equal to unity. Since the Magellanic Clouds are in fact characterized by low C and O abundances and also by low [C]/[O] ratios (Dufour, Shields, and Talbot 1982; Dufour 1984), this is not a likely situation. Let us, by way of illustration, assume that the CO abundance is governed by the C abundance alone. This then implies CO underabundances of A(CO) = 4 in the LMC and A(CO) = 20 in the SMC. Hence, the curves in Figures 3 and 4 would be valid up to $f_{UV} = 2.7$ for the LMC and $f_{UV} = 13$ for the SMC. Now only the cases $N(M) \propto M$ and $N(M) \propto M^{-1}$ would fit both SMC and LMC; they would indicate larger clump masses for the LMC than for the SMC.

We thus conclude that, whether CO is self-shielding or not, a likely range of clump parameters exists for which the conditions observed in the Magellanic Clouds (high UV intensities, low dust-to-gas ratio, low metallicity) lead to relatively low CO intensities. This conclusion can be verified by, e.g., ^{13}CO observations. The combined effects of f_{UV} and abundance should lead to ^{12}CO/^{13}CO ratios higher than those found in the solar neighborhood by a factor of 3 or more in the LMC and by a factor of 20 or more in the SMC. It is even conceivable that in the SMC, CO depletion is so severe that a significant fraction of the ^{12}CO emission is *optically thin*. This could be verified, again by ^{13}CO observations, or, perhaps more easily, by comparing ^{12}CO emission in the J = 1–0 and J = 2–1 transitions in similar beams.

Some further comments are in order. First, H_2 is self-shielding and has very high grain-surface formation rates. Thus, at least moderate amounts of dust depletion will not affect H_2 abundances. At the same time, we have argued that CO will be depleted with respect to H_2 both because of a low C abundance/low [C]/[O] ratio and because of enhanced photodestruction rates. Consequently, the solar neighbourhood conversion of ^{13}CO to H_2 column densities [$N(H_2)/N(^{13}CO) = 5 \times 10^5$; Dickman, 1978] that is normally used to obtain H_2 will significantly underestimate the amount of H_2 actually present. Indeed, relatively strong (excited) H_2 emission has now been found toward several LMC and SMC H II regions that show no or very weak CO emission (Israel and Koornneef 1986). This conclusion applies not only to the Magellanic Clouds, but to any location in a galaxy (including ours) that has metallicity or dust abundances or both lower than does the solar neighborhood.

Second, in the model outlined above, CO has a low abundance *and* a low rate of occurrence as a consequence of low element abundances, low dust abundances, and a strong UV field. These conditions are typical of galaxies with intermittent bursts of star formation, during a burst phase (e.g., as predicted by models of stochastic star formation; Gerola and Seiden 1978; for the Magellanic Clouds see also Matteucci and Chiosi 1983). The relative amplitude of intermittent star formation processes is greatest for low-mass galaxies. When such galaxies are in a quiescent phase, low element and dust abundances still apply, but the lack of short-lived OB stars implies a low value for the UV radiation field energy density U'_{UV}, so that in turn f_{UV} may drop well below unity. One could thus envision the existence of quiescent (nonblue) irregular dwarf galaxies characterized by low metallicity and dust levels but a high CO content at least relative to active (blue) irregular dwarf galaxies. In other words, dwarf galaxies with high *present* star formation rates would be poor prospects for CO observations as compared with dwarf galaxies with *low* present star formation rates. This proposition is open to observational verification.

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