INTERSTELLAR GAS IN THE MAGELLANIC CLOUDS: SEST OBSERVATIONS OF CO AND OTHER MOLECULES

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ABSTRACT. The first results based on SEST observations of CO and other molecules in the Magellanic Clouds are presented. The properties of the CO emission, CO isotopic ratios and the conversion factor between CO emission and H_2 column density are discussed. Abundances of detected molecules are estimated and compared with those in Galactic molecular clouds.

The different star formation histories in the Galaxy and the Magellanic Clouds, manifested by the different heavy elemental abundances, should be reflected in the chemical composition of the gas. The Galaxy and its satellites seem to form a sequence in the sense of formation and destruction rates of molecules, with the SMC showing the most hostile environment and the LMC being an intermediate case. Thus, observations of the interstellar gas in this sample of galaxies have the prospect to distinguish the impact of the radiation field, and the elemental and dust abundances on the chemistry and physical properties of the gas. Crucial in this context is the proximity of the Magellanic Clouds which with present day receivers and large telescopes (notably the Swedish-ESO Submillimetre Telescope) enables detailed investigations of individual molecular clouds in these objects.

This paper presents a short review, and the first observational results obtained with the SEST, of the interstellar gas in the Magellanic Clouds.

1. Global Properties of the Magellanic Clouds

The centroid distances of the LMC and the SMC, derived basically from Cepheids, are 50 and 60 kpc, respectively, with uncertainties of about 10% (Feast, 1988). On the assumption of a circular disc the inclination of the LMC is estimated to be $27^{\circ} \pm 2^{\circ}$(de Vaucouleurs and Freeman, 1972) from optical and radio isophotes; photometric observations of Cepheids give consistent results although they suffer from considerably larger errors (Feast, 1989). Crude estimates of the scale height of the disc in the LMC range from about 200 pc to 1 kpc for the youngest population to the oldest Miras, respectively (Feast, 1989).

The SMC is more oriented along the line of sight with a total depth of 15 to 20 kpc, derived from Cepheids (Caldwell and Coulson, 1986; Welch et al., 1987). Martin et al. (1989) conclude that the total depth of young stars is 10 kpc or less, a value that should apply to the molecular clouds as well. Thus, in contrast to the Galaxy, parameters of the molecular clouds in the Magellanic Clouds do not suffer from significant uncertainties with respect to distances.

Table 1 summarizes mass estimates of individual interstellar components collected from the literature. The molecular masses are inferred from large scale CO observations made with the

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Columbia 1.2 m telescope. To convert from CO luminosity to H_2 mass, conversion factors substantially larger than that derived for the Galaxy have been applied: higher by a factor of 6 for the LMC (Cohen et al., 1988) and 20 for the SMC (Rubio et al., 1990).

Table 1. Mass estimates in the Magellanic Clouds (in units of M_O)

	LMC	SMC	References
Total (dynamical)	6.1×10^9	1.8×10^9	Lequeux, 1984
HI + He	7.0×10^8	6.5×10^8	Lequeux, 1984
H_2	1.4×10^8	3.0×10^7	Cohen et al.,1988; Rubio et al.,1990
Gas / Total	14 %	38 %	
Molecular / Atomic	20 %	5 %	
Dust	$(3.5\text{-}7.5)\times10^5$	$(2.0\text{-}4.6)\times10^4$	Schwering,1988
Gas / Dust (relative to the Galaxy)	4 [a]	10-17 [a]	Lequeux,1984; Koornneef,1984; Martin et al.,1989
	2-6 [b]	15-80 [b]	Schwering,1988

[a] $N(HI)/E_{B\text{-}V}$ [b] mass ratio

Table 2 lists the deficiencies of the C, N and O abundances in the Magellanic Clouds, determined for HII regions, relative to those in the Orion nebula. The original data were tabulated by Dufour (1984), however, the slightly revised values by Dennefeld (1989) are used here. Improvements of the ionization correction factors and atomic coefficients account for the differences. It should be added that observations indicate a large overdeficiency of carbon in HII regions compared with that in F-type supergiants (Spite et al., 1989; Russell and Bessell, 1989), possibly connected to the grain formation processes (Russell and Bessell).

The dissociation of interstellar molecules is largely governed by the ambient UV radiation field and the degree of dust shielding. To estimate the CO depletion in the Magellanic Clouds, Israel et al. (1986) define a parameter, f_{UV}, representing the penetrating power of the ambient UV field. They find f_{UV} factors of 4.5-7.5 (LMC) and 8.5-17.5(SMC) higher than in the Galaxy. Using a chemical model, Maloney and Black (1988) calculate the H_2 density and the fraction of carbon in CO under conditions relevant to the Galaxy and the Magellanic Clouds. In spite of the significantly different environments the H_2 is essentially unaffected in the sense of peak abundance and extent in sharp contrast to the behaviour of CO; in the SMC the fraction of carbon tied up in CO is two orders of magnitudes less than in the Galaxy. These results suggest that readily detectable molecules like CO may have progressively lower column densities in molecular clouds of comparable sizes in a sequence from the Galaxy to the SMC.

Molecular hydrogen has been detected from shocked gas and UV-illuminated cloud surfaces in the Magellanic Clouds at 2 µm (Koornneef and Israel, 1985; Israel and Koornneef, 1988). Molecules detected in the LMC at cm wavelengths are OH, CH and H_2CO (see e.g. Gardner, 1984), and masers of OH (Caswell and Haynes, 1981; Haynes and Caswell, 1981) and H_2O (Scalise and Braz, 1982; Whiteoak et al., 1983; Whiteoak and Gardner, 1986). An H_2O maser is also observed in the SMC. At mm wavelengths the lowest rotational transition of HCO^+ (Batchelor et al., 1981) and CO (see e.g. the review by Israel, 1984) have been detected, the former only in the LMC and the latter also in the 2-1 transition in both Clouds (Israel et al., 1986). It is probably significant in the context of molecular abundances that, excluding maser transistions, only H_2 and CO are detected in the SMC.

The Magellanic Clouds have been more or less fully mapped in the CO(1-0) transition by Cohen et al. (1988) and Rubio et al. (1990). In the LMC Cohen et al. mapped an area of 6°x6° with a gridpoint spacing equal to the beamsize (8.8 arcmin) and detected CO emission in about 10% of this region. As in the Galaxy they find a close correspondence of CO emission and Population I objects. From a comparison of the CO luminosity-linewidth relation observed in the Galaxy and in the

Table 2. Deficiencies of elemental abundances in Magellanic Cloud HII regions relative to Orion (Dennefeld, 1989).

	LMC	SMC
[C/H]	3.3	16
[N/H]	4.4	14
[O/H]	1.4	3.7

LMC, Cohen et al. estimate the conversion factor from CO emission to H_2 column density to be 6 times higher in the LMC. Applying this conversion factor they find that the ratio of molecular to atomic mass is about 30% (in the observed region). Rubio et al. (1990) arrive at a significantly larger conversion factor for the SMC, about a factor of 20 higher than in the Galaxy.

2. SEST Observations of CO in the Magellanic Clouds

The studies of the CO emission in the Magellanic Clouds is a SEST key programme carried out by a consortium of astronomers from the Swedish and ESO communities (see Israel and Johansson, 1989). The idea is to fully sample the $^{12}CO(1\text{-}0)$ emission, and to observe higher transitions and less common isotopes in selected regions. The key project was initiated in April 1988, however, previous to that two smaller areas in the 30 Dor region were mapped during the comissioning phase of SEST (Johansson and Booth, 1989; Johansson et al., 1989; Johansson et al., in preparation).

The survey in the 1-0 line uses frequency switching, a grid point spacing of 20" (FHPBW= 43"), and a 3σ detection limit of about 0.15K for the LMC and 0.10K for the SMC. During the first two years of operation some 5000 positions have been observed. Sample contour maps of the velocity integrated CO emission in the LMC are shown in Fig. 1.

The key project data of the SMC are discussed by Rubio in these proceedings.

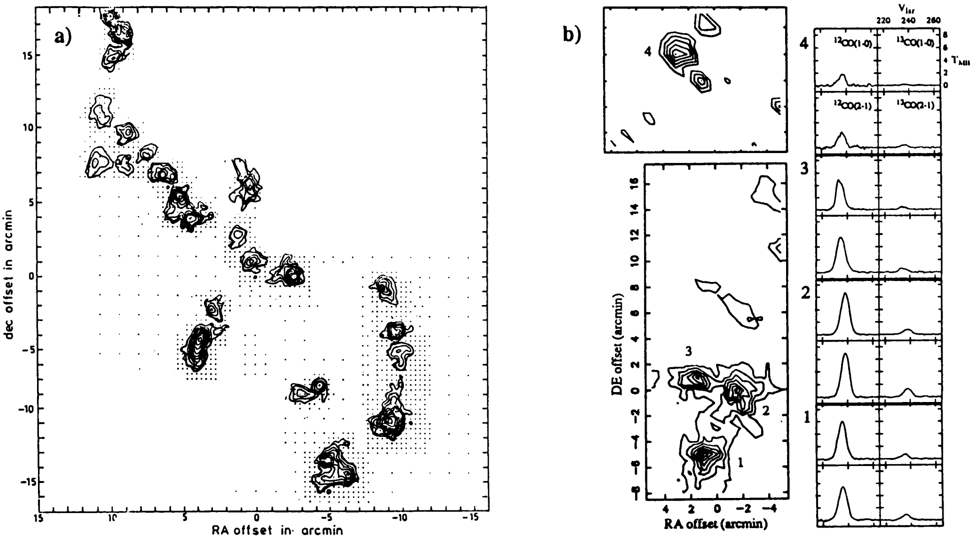

Figure 1. Maps of the velocity integrated CO(1-0) emission in the N11 (a) and the 30 Dor (b) regions. The four major clouds in the 30 Dor area (see text) are labelled and the corresponding spectra observed in the two lowest rotational transitions of ^{12}CO and ^{13}CO are shown.

2.1. CO EMISSION PROPERTIES IN THE LMC

The following discussion is based on the data collected in the 30 Dor region, an area that may not be representative of the LMC due to the very intense UV flux and thus most likely high CO dissociation rates. However, cloud 1 (see Fig. 1b) which is examined in some detail shows dark cloud properties in the sense that no internal heating source is evident from the IRAS data

(Schwering, 1988), in contrast to the three other clouds in the sample discussed below. Particulary cloud 4 which is centered on the 30 Dor nebula (on the sky) is probably influenced by this huge HII region.

A first indication of low CO abundances in the LMC is possibly the observed $^{12}CO/^{13}CO$ linewidth ratios in positions within 1' from the centres of clouds 1 and 2 (see Fig. 1b): typically 1.15 with no definite tendency to vary with position. Values representive of the Galaxy are rather in the range 1.5 - 2. If this is a line saturation effect the ratios above suggest lower CO abundances in the LMC relative to the Galaxy.

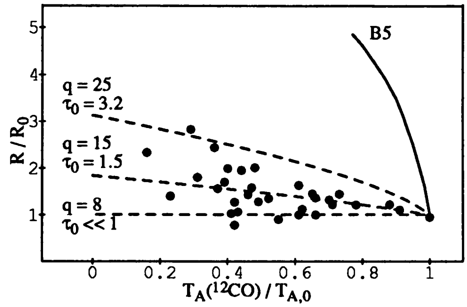

Figure 2. The $^{12}CO/^{13}CO$ antenna temperature ratio (R) versus the ^{12}CO temperature, normalized to the quantities observed in the cloud centre (R_0 and $T_{A,0}$, respectively). The dots represent the observed ratios in the LMC and the solid line the Galactic cloud B5. The dashed lines are derived assuming LTE conditions (see text) for three $^{12}CO/^{13}CO$ abundance ratios (q) and the corresponding ^{12}CO peak optical depths (τ_0).

Fig. 2 shows the ratio of the $^{12}CO/^{13}CO$ peak antenna temperatures versus that of the ^{12}CO line for the same sample of positions as above. To enhance the effect of possible line saturation both quantities are normalized to the values observed at the cloud centres. For comparison, the full line shows this function for the Galactic globule B5, estimated from data published by Langer et al. (1989). B5 represents a cloud which suffers from a high degree of ^{12}CO line saturation in the central portions. The dashed lines refer to the simplified assumption of LTE conditions using the following equations

$$T_A = T_{ex}(1-e^{-\tau})$$

$$\tau(^{13}CO) = \tau(^{12}CO)/q$$

where T_{ex} is the excitation temperature, τ the optical depth, and q the $^{12}CO/^{13}CO$ abundance ratio. In addition to the low optical depths suggested by Fig. 2, significantly lower CO isotopic ratios in the LMC than in the Galactic disc (Penzias, 1980) are implied. However, note that it is possible to retain strongly saturated lines and still resemble the LMC data in this plot by including the effect of kinetic temperature variations.

Towards the four major CO peaks in Fig. 1b, the ^{12}CO and ^{13}CO isotopes in the two lowest rotational transitions have been observed. All spectra, inserted in Fig. 1b, refer to the CO(1-0) beamsize. The intensity scales are in main beam brightness temperature units. To solve for CO abundances and isotopic ratios we have used the standard large velocity gradient (LVG) approximation (see e.g. Goldsmith et al., 1983). The model parameters are constrained by the observational errors and upper limits of the kinetic temperatures. As a guidance for the latter constraint we use estimates of the dust temperatures (Schwering, 1988). The diameters in this cloud sample are in the range 8-20 pc. Combined with the observed linewidths we find global velocity gradients between 0.4 and 1.1 km s^{-1} pc^{-1}, i.e. similar to those observed in CO in the Galaxy. The corresponding photon thermalization length is less than 1 pc, indicating that the LVG approximation is justified. The LVG solutions are presented in Table 3. In all four cases the column densities of ^{12}CO are significantly lower than in the Galaxy for clouds of similar sizes, which is also reflected in the low optical depths derived. The isotopic ratios obtained with the LVG model are in surprisingly good agreement with those suggested by Fig. 2 (from a completely different sample and line of interpretation). This applies to the optical depths as well. It is interesting to note that our sample of clouds seems to resemble the translucent and high latitude clouds in the Galaxy studied by van Dishoeck et al.(1991) in the sense of CO column densities and, possibly, isotopic ratios.

One obvious source of error not accounted for in the LVG model is the homogeneity of the parameters, notably, kinetic temperature and density. Selfabsorption, for example, could give

Table 3. LVG solutions defined by the main beam brightness temperatures in the two lowest rotational transitions of ^{12}CO and ^{13}CO. The parameter space is constrained by the observational errors (1.5σ) and kinetic temperatures less than 40K (clouds 1–3) and 70K (cloud 4).

	Cloud 1	Cloud 2	Cloud 3	Cloud 4
Beam filling factor	1.0 – 0.3	1.0 – 0.4	1.0 – 0.4	0.20 – 0.05
$\log(N_{CO} / cm^{-2})$ [a]	16.9 – 17.4	16.9 – 17.1	16.6 – 16.9	16.5 – 16.7
^{12}CO(1-0) optical depth	1.0 – 3.5	0.7 – 1.3	0.2 – 1.0	0.4 – 1.1
Kinetic temperature [K]	11 – (40)	14 – (40)	12 – (40)	20 – (70)
$\log(n_{H_2} / cm^{-3})$	3.2 – 4.4	3.5 – 5.5	3.4 – 5.5	4.0 – 5.3
Isotope ratio ($^{12}CO/^{13}CO$)	12 – 50	11 – 19	12 – 25	14 – 26

[a] Column density averaged over the CO(1-0) beam

largely misleading results. However, such features are expected to be localized and thus significantly beam diluted in the LMC. Similarily, regions of strongly saturated ^{12}CO lines might well be present but do not seem to dominate the emission.

In cloud 2 weak $C^{18}O$ lines have been detected in the 1-0 and 2-1 transitions, which translates to a $^{13}CO/C^{18}O$ abundance ratio of 20±5 (25 and 14 for the 1-0 and 2-1 lines, respectively). The corresponding $^{12}CO/C^{18}O$ abundance ratio in cloud 2 is then 300±150.

2.2. THE CONVERSION FACTOR FROM CO EMISSION TO H_2 COLUMN DENSITY

Since CO observations are by far the dominant way to estimate masses of the molecular gas in galaxies, the possible variation of the conversion factor with galaxy type (see e.g. Israel, 1988) needs to be examined. While the conversion factor for the Galaxy is considered to be accurate to within a factor of a few, and likely can be applied to late type spirals with some confidence, there are indications of substantially higher conversion factors in, e.g., the Magellanic Clouds (Cohen et al., 1988; Rubio et al., 1990). It is theoretically well established that the conversion factor is a function of cloud parameters (Kutner and Leung, 1985; Maloney and Black, 1988), e.g., in case of virialized clouds and thermalized CO transitions it is proportional to $n^{0.5}/T_R$ (van Dishoeck and Black, 1987), where n is the average H_2 density and T_R the radiation temperature of the CO line. This simple dependence may not apply to the Magellanic Clouds as suggested in the preceeding section. The variation of the conversion factor with the CO fractional abundance is probably more enlightening in this context. To estimate this dependance we have used the LVG model and normalized the solution to a "standard cloud" in the Galaxy with a conversion factor of $3\ 10^{20}$ $cm^{-2}\ (K\ kms^{-1})^{-1}$, a radiation temperature of 10 K, and a CO fractional abundance of $8\ 10^{-5}$. Fig. 3 shows the results for three different H_2 densities. LVG solutions for Galactic clouds generally give H_2 densities greater than $10^3\ cm^{-3}$, suggesting that the fractional abundance of CO can be at least an order of magnitude lower relative to the Galaxy without any noticeable change in the conversion factor.

In an attempt to derive the conversion factor in the LMC we have used the concept of virial masses to estimate H_2 masses, although several authors have questioned its applicability (e.g. MacLaren et al., 1988; Maloney, 1990). In particular, Maloney states that virial masses do not provide an estimate of the conversion factor, but that the correlation found between CO emission and virial masses (e.g. Solomon et al., 1987) is implied by the size-linewidth relation observed for molecular clouds. On the other hand, Maloney also points out that the conversion factor derived by Solomon et al. agrees well with that obtained from γ-rays for clouds

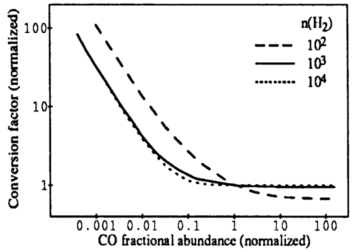

Figure 3. The conversion factor of CO emission to H_2 column density versus n_{CO}/n_{H_2},(see text).

more massive than about 10^5 M_o. This limit applies to the most massive LMC clouds in the sample discussed below. Maybe more important is the fact that the quantities derived, in effect, are relative to those of the Galaxy. This is provided that possible systematic differences between the samples and methods of analysis are identified and accounted for.

The LMC sample consists of 23 clouds distinguished in the areas shown in Fig. 1b. The plot of virial masses against CO luminosities and the size-linewidth dependence for this sample are displayed in Fig. 4a and b, respectively. Two clouds differ significantly from the rest of the sample in both plots. Positional coincidences on sky suggest that one is closely associated with the 30 Dor nebula, the other one with the HII region N159. Combined with their positions in the size-linewidth plot, this suggests that appreciable amounts of energy is injected into these clouds and accordingly their virial mass estimates are not meaningful. While the size-linewidth relations, within the errors, are identical for the LMC and the Galaxy, Fig. 4a indicates a conversion factor higher by a factor of about 1.5 in the LMC. Allowing for possible systematic differencies in the two samples like the intensity calibrations and methods to derive the quantities, a factor between 1 and 2 higher than in the Galaxy seems eligible.

Provided that the optical depths derived in the preceeding section are about correct, it seems unavoidable to introduce a correction to the virial masses (relative to the Galaxy) to account for molecular mass not detected in the LMC. The critical density for significant excitation of the CO is given by $n^*=A/(\tau<\sigma v>)$, where A, τ, σ, and v is the Einstein coefficient, the optical depth (for optical depths smaller than 1, τ is replaced by 1), the collisional cross section, and the thermal velocity of hydrogen, respectively. With respect to excitation conditions the ^{12}CO lines in the LMC seem to resemble the ^{13}CO lines in the Galaxy. It is known that linewidths as well as sizes (from half intensity contours) of molecular clouds in the Galaxy are smaller when defined by ^{13}CO observations than the corresponding ^{12}CO values. MacLaren et al. (1988) find a linewidth ratio ^{12}CO/^{13}CO of 1.4 on the average for a small sample of clouds. A typical ratio for the sizes seems to lie in the range of 1.5 to 2 (see e.g. Snell, 1981). If these numbers generally apply, the size-linewidth relation will be largely indistinguishable whether it is defined by ^{12}CO or ^{13}CO observations. In contrast, the virial mass formula gives a factor of 3 or 4 higher values when ^{12}CO quantities are entered. Owing to this effect, a conservative estimate yields a conversion factor in the range 1 to 6 higher in the LMC relative to the Galaxy.

An estimate of the fractional abundance of CO, averaged over the fraction of the cloud where CO is detected, have been obtained from the CO luminosities (assuming an optical depth of 1) and the virial masses. The clouds in our sample cluster around $10^{-5.4}$, a factor of about 10 less than the value commonly quoted for the Galaxy.

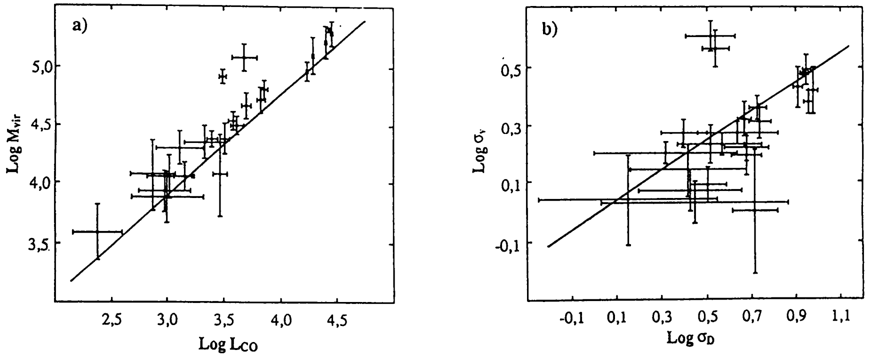

Figure 4 Plots of the virial masses versus CO luminosity (a) and the size-linewidth dependence (b) for a sample of LMC clouds. The corresponding Galactic relations obtained by Solomon et al. (1987) are shown as solid lines.

3. Other molecules in the Magellanic Clouds

Table 4 summarizes the SEST detections of molecules other than CO in the Magellanic Clouds. The data refer to clouds associated with (seemingly) the HII regions N159 (cloud 2 in Fig. 1b) and N19, in the LMC and the SMC, respectively. Only a few molecular transitions have been searched in the SMC; when detected the intensities are at least a factor of 6 less than observed in the LMC. This emphasizes the previous experience of a lower detection rate in the SMC relative to the LMC.

To calculate molecular abundances we have made the following assumptions: (i) the detected transitions have small optical depths, (ii) a Boltzmann distribution of the populations defined by a temperature in the range 5–50 K, and (iii) the spatial extent of the emission from a particular transition relative to the CO extent is the same as for Galactic clouds. A preliminary search through the literature on Galactic clouds suggests that the emission areas (defined by the half intensity contours) of our detected lines relative to that of CO are of the order of 0.1 or higher, with one exception, SO. For SO we have applied a factor in the range 0.1 to 0.01, otherwise the range used is 1 to 0.1. In the calculations of abundances relative to CO, these factors are simply introduced as beam filling factors. The ranges in the kinetic temperatures and the beam filling factors above define the uncertainties of the derived abundances. The last three columns in Table 4 give the abundances of the molecules detected relative to CO (assuming the properties indicated by our LVG solutions) for the LMC as well as for two Galactic clouds, Orion and TMC 1.

Due to the assumptions above and uncertainties not accounted for, e.g., different peak positions of the individual transitions, a comparison with chemical models is not meaningful at this stage. However, the general tendency is that abundances of the detected molecules, relative to CO, scale in about the same way in the LMC as in the Galaxy. The possible exception is SO, the only molecule in our sample which is not carbon bearing.

A more detailed analysis of these data is in preparation (Johansson et al.; de Graauw et al.).

Table 4. Data on molecular transitions detected in the Magellanic Clouds.

Molecule	Freq. [GHz]	SMC T_{MB} [K]	LMC T_{MB} [K]	LMC $\log[N_X/cm^{-2}]$ a	LMC $\log[N_X/N_{CO}]$ b	Orion $\log[n_X/n_{CO}]$ c	TMC 1 $\log[n_X/n_{CO}]$ c
CS(2-1)	98	0.05	0.30	13.0 – 13.4	-4.0 – -2.6	-4.6 – -4.0	-4.8 – -4.2
CS(5-4)	245	-	0.14	12.5 – 14.3	-4.5 – -1.7		
CN(1-0)	113	<0.03	0.11	12.7 – 13.1	-4.3 – -2.9	-4.5 – -3.9	-3.6 – -3.0
CN(2-1)	227	-	0.11	12.4 – 12.9	-4.5 – -3.1		
$SO(3_2-2_1)$	99	-	0.08	12.6 – 12.9	-3.4 – -2.1	-5.2 – -4.6	-4.4 – -3.8
$HCO^+(1-0)$	89	0.07	0.48	12.8 – 13.3	-4.2 – -2.7	-4.6 – -4.0	-4.2 – -3.6
HCN(1-0)	89	<0.02	0.16	12.5 – 13.0	-4.5 – -3.0	-4.3 – -3.7	-4.0 – -3.4
HNC(1-0)	91	-	0.12	12.1 – 12.6	-4.9 – -3.4	-5.3 – -4.7	-4.2 – -3.6
$C_2H(1-0)$	87	-	0.10	13.4 – 13.9	-3.6 – -2.1	-4.3 – -3.7	-4.1 – -3.5
$H_2CO(3_{1,2}-2_{1,1})$	226	-	0.12	12.7 – 13.9	-4.3 – -2.1	-3.8 – -3.3	-4.0 – -3.4
$C_3H_2(2_{1,2}-1_{0,1})$	85	<0.08	0.09	12.4 – 13.4	-4.6 – -2.6	-	-

[a] Beam averaged column densities, calculated for Boltzmann temperatures in the range 5–50 K

[b] $N_{CO}=10^{17}$ cm^{-2}; beam filling factors relative to CO applied (see text)

[c] Fractional abundances relative to CO derived from the data published by Blake et al. (1987)

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