

CARBON MONOXIDE IN THE MAGELLANIC CLOUDS

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1. Introduction

Molecular gas is a major constituent of the interstellar medium of all late-type galaxies. Virtually all of it is in the form of cold molecular hydrogen (H_2) which today cannot be observed directly. However, the tracer molecule carbon monoxide (CO) (relative abundance 10^{-5}) is easily detected. For the Magellanic Clouds (MCs), CO studies are of specific importance. The Clouds are rich in HI, and if we can establish the presence of significant amounts of H_2 as well, this will influence our estimates of the global rate of star formation and its history. Complexes of presently quiescent molecular gas may betray regions primed for star formation, but not yet in action. Detailed studies of the HI, HII and H_2 and young star content may provide estimates of star formation efficiencies on scales of a kiloparsec.

There is another important aspect. At present a controversy rages on how to estimate H_2 amounts from observations of the optically thick molecule CO. At the core of this controversy lies the question: to what extent does the CO emission from H_2 clouds reflect variations in dust content, metallicity and the ambient UV radiation field (cf. Israel 1988). Here, the MCs are important because of their physical condition: metallicity lower and radiation field somewhat higher than in the Galaxy. They thus provide a good laboratory in which to test environmental effects.

The MCs present both a global and a detailed view. Today, millimetre telescopes offer linear resolutions better than about 15pc. This is much higher than presently obtainable far-infrared (FIR) or HI resolutions.

2. History

Before 1980, little was known about CO or H_2 in the MCs (cf. Israel 1984). The first CO detection in the LMC (Huggins *et al.* 1975) was followed by a limited CO(2-1) survey (Israel *et al.* 1982, 1986). Although only a minute fraction of the LMC and SMC was sampled, it was clear that in the Clouds, especially the SMC, CO emission is weak compared to the Galaxy. This is

explained by CO photodissociation due to the strong radiation field, low dust content and low metallicity of the Clouds. The weakness of CO does not imply small amounts of H₂; molecular hydrogen is only weakly affected by photodissociation in the Clouds.

The first complete CO map of the LMC, produced by Cohen *et al.* (1988) with a linear resolution of 200 pc, shows CO clouds near major star formation regions such as N11. The Bar can be recognized but 30 Doradus is weak in CO. In contrast, the region south of 30 Doradus, notably near N159, shows strong CO emission extending southwards from the HII regions to an optically inconspicuous area. This may be the major star formation region of the future. The CO map is very similar to the warm-dust map published by Schwering (1988) but differs from the HI map (Rohlfs *et al.* 1984). Cohen *et al.* (1988) conclude that for a given amount of H₂, CO emission in the LMC is about six times weaker than in the Galaxy. Thus, use of the Galactic conversion leads to an underestimation of H₂, as also concluded by Israel *et al.* (1986).

3. The SEST Key Project

Recently, the Swedish-ESO millimetre telescope SEST has become available at ESO. With its 40" beam, mapping the MCs is time consuming. For this reason, a consortium of ESO and Swedish observers was formed. ESO and Sweden have rewarded the consortium with Key Project status, guaranteeing a continuation of the study of CO in the Clouds. In the following, we present preliminary results from the initial Swedish work and the work done until now by the consortium. So far, several molecular clouds associated with the Doradus HII regions, including 30 Doradus itself, have been mapped in the LMC, as well as a small cloud near N55, and a large complex associated with N11.

We have also obtained a several-degrees-long stripmap at constant R.A. through the Doradus region and have started mapping clouds found in this strip. A similar degrees-long strip through Doradus and the Bar, at constant Dec, is now in progress. In the SMC, we have mapped a few isolated small clouds, notably N88, and a map of the relatively bright southwestern part of the Bar is in progress. We have also conducted a survey of selected positions in the Clouds. The presence of IRAS infrared peaks gives a much better chance of detecting CO than the presence of dark clouds or HII regions *per se*. Thus, in the LMC survey (which took place after the SMC survey), we concentrated on the IRAS peaks given by Schwering and Israel (1990). We also measured ¹³CO strengths on the brightest ¹²CO peaks. The survey yielded, in the LMC, 75 ¹²CO detections, 10 upper limits and 36 ¹³CO measurements and, in the SMC, 18 ¹²CO detections, 17 upper limits and 6 ¹³CO measurements.

4. Results of the preliminary CO survey

Although IRAS sources give a good chance of detecting CO, the CO/FIR ratio has a large scatter. Much of this is caused by the different IRAS and SEST beam sizes, but at least part of it is intrinsic. It appears that the integrated CO emission is better correlated with dust temperature than with dust column density. CO emission peaks at dust temperatures between 35 and 40K. At higher temperatures emission drops, presumably because photodissociation starts dominating.

We confirm the remarkable weakness of CO in the Clouds. Our survey is biased towards the strongest CO sources in the Clouds. Yet, we find a mean detected integrated CO strength of only 11 K km s⁻¹ in the LMC and 3 K km s⁻¹ in the SMC. Comparison with 'average' Galactic positions observed with the same linear beamsize yields a mean of 30 K km s⁻¹ for the latter. Only seven (10%) LMC detections are at this brightness level; none in the SMC. Thus, CO in the LMC

is at least three times weaker than Galactic CO, whereas CO in the SMC is at least ten times weaker!

In the Clouds, the $^{12}\text{CO}/^{13}\text{CO}$ isotopic ratio is about 10 for the peaks and 14 for integrated profiles, as compared to peak ratios between 5 and 8 in the Galaxy. In the LMC, peak ratios range from 7 to 14. Statistics for the SMC are still too poor for a conclusion. We have calculated H_2 column densities both from integrated ^{12}CO intensities and from ^{12}CO and ^{13}CO measurements. Surprisingly, the two H_2 column density sets are not linearly related. Rather, ^{13}CO -inferred H_2 column densities increase only very slowly with ^{12}CO -inferred H_2 column densities. Thus, meaningful H_2 column densities and masses can only be obtained from modelling; use of the Galactic conversion leads to false results.

5. Maps of giant molecular cloud complexes

So far, only a small fraction of the Magellanic Clouds has been mapped. Here, we briefly discuss three maps. A preliminary map of the Doradus HII regions was made by the Swedish observers during commissioning time. They found six major CO clouds and a dozen lesser ones, and used Local Velocity Gradient models to conclude that the $J=1-0$ ^{12}CO has small optical depths around unity in these clouds, that the fractional abundance of ^{12}CO is only one tenth of that in the Galaxy, and that for a given amount of H_2 , CO emission from these clouds may be up to six times weaker than from Galactic clouds. The latter conclusion confirms the results obtained by Israel *et al.* (1986), Cohen *et al.* (1988) and also the result mentioned in section 4.

The consortium has mapped most of the HII region complex N11 (Fig. 1). In a region of about 500×500 pc, we find 21 well-separated CO clouds, of typical size 20-30 pc. The structure of the N11 complex is similar to that of the 200 pc diameter Orion molecular complex. Between bright filaments and clumps, the Orion map shows weaker emission not seen in N11, probably because of sensitivity limitations. The clouds follow the IRAS infrared map closely, especially at 25 and 60 μm . In the southwest, CO clouds form a 'ring' around a rich cluster of luminous stars; apparently all the CO there has been consumed, destroyed or driven out.

Mapping of the weak CO clouds in the southwest bar of the SMC is still in progress. Several clouds at different radial velocities have been found near major IRAS sources (Fig. 2). The southwest Bar is a confused area because here the line of sight through the SMC is kiloparsecs long. Indeed, individual clouds overlap in integrated CO maps. They must be carefully separated in position-velocity space before, for example, virial masses can be obtained.

6. Molecular cloud masses

For about 50 LMC clouds, mostly in two complexes (Doradus and N11) we can compare the virial and the CO mass derived in the usual manner. In principle both should be independent of actual CO abundance. We find that in the (virial) mass range of $2 \times 10^3 M_\odot$ to $2 \times 10^5 M_\odot$, virial mass is higher by a factor of 1.5 to 6 with a mean of 3 times higher. Masses derived from both ^{12}CO and ^{13}CO are lower than the virial mass by a factor of 5 to 10, although this is not independent from abundances. Moreover, the ratio between the derived masses depends on (virial) mass. This is the same effect already mentioned in section 4. Although a final conclusion awaits proper modelling, taking into account the physical environment, it appears that H_2 masses and column densities in the LMC are comparable to those of Galactic molecular clouds, whereas the CO-to- H_2 conversion

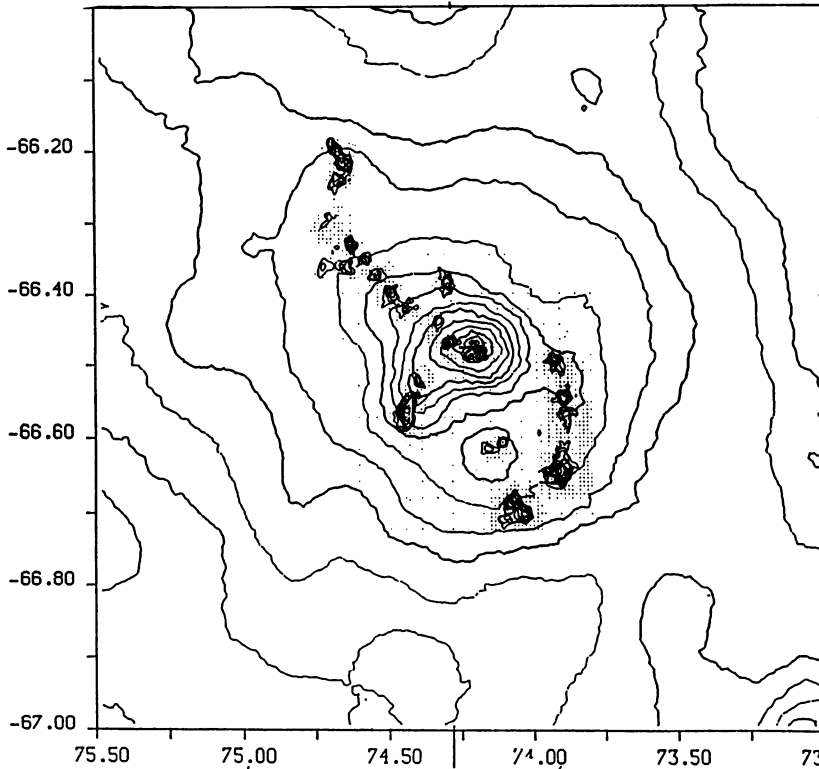


Figure 1. Map of CO clouds in N11 superposed on GEISHA 100 μm IRAS map. Distribution of CO clouds follows the (lower resolution) infrared contours. Positions sampled for CO are indicated by dots; 1950 coordinates are given in degrees.

factor is about three times higher than in the Galaxy. As the virial mass was estimated conservatively, this factor is more likely to be higher than lower. This result can be plausibly ascribed to relatively important photodissociation in the LMC (cf. Israel *et al.* 1986). To resolve this issue, modelling of the sort discussed by Maloney (1990) is an urgent necessity.

7. Summing up

The results obtained confirm that the CO emission from the Clouds is weaker than that from the Galaxy by a significant factor, for given amounts of H_2 . At least the LMC contains almost certainly 'normal' amounts of H_2 . Molecular complexes in the LMC and SMC consist mostly of 20-30 pc-sized clouds, although observations at higher resolutions probably will show important substructure in these clouds. Many questions still need to be answered. What will modelling tell us about the quantitative influence of environmental conditions on LMC molecular cloud properties? Do cold CO clouds not engaged in star formation ('Taurus dark clouds') exist? What is the condition of molecular clouds in the extreme environment of the SMC? What can we conclude on the interaction between molecular clouds and star formation?

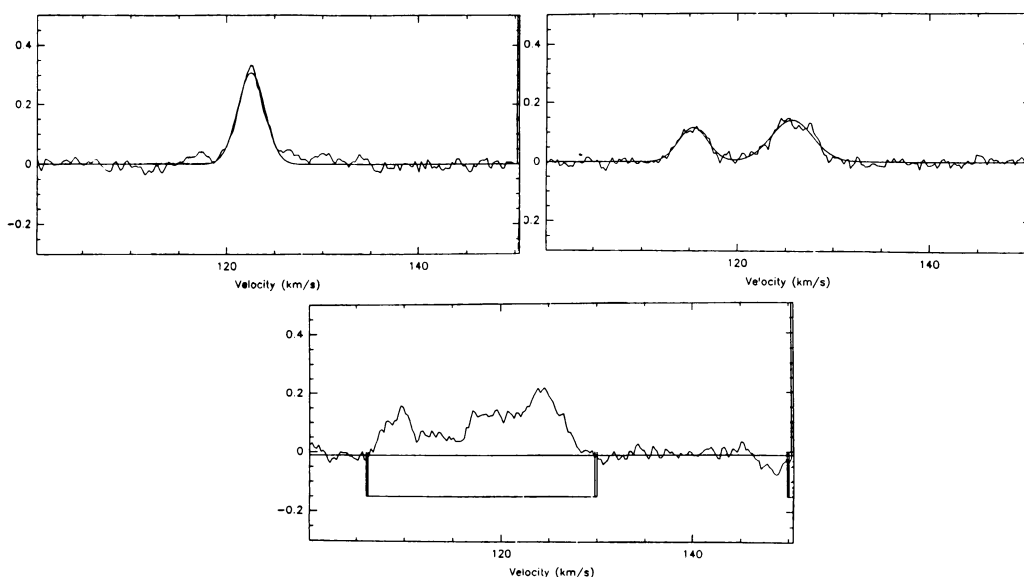


Figure 2. CO profiles of cloud peaks in the SMC southwest Bar. Individual clouds are well defined in top profiles, but bottom profile shows at least three confused components. CO intensities are in K, not corrected for main-beam efficiency.

8. References

- Cohen, R.S., Dame, T.M., Garay, G., Montani, J., Rubio, M., Thaddeus, P. (1988), *Ap. J.* **331**, L95.
- Huggins, P.J., Gillespie, A.R., Phillips, T.G., Gardner, F., Knowles, S. (1975), *M.N.R.A.S.* **173**, 69P.
- Israel, F.P. (1984), *IAU Symp 108 Structure and Evolution of the Magellanic Clouds*, S. van den Bergh, K.S. de Boer (eds.) (Reidel: Dordrecht) p.139.
- Israel, F.P. (1988), *Millimetre and Submillimetre Astronomy*, R.D. Wolstencroft, W.B. Burton (eds.) (Kluwer: Dordrecht) p.281.
- Israel, F.P., de Graauw, Th., Lidholm, S., van de Stadt, H., de Vries, C. (1982), *Ap. J.* **262**, 100.
- Israel, F.P., de Graauw, Th., van de Stadt, H., de Vries, C.P. (1986), *Ap. J.* **303**, 186.
- Maloney, P. (1990), *The Interstellar Medium in Galaxies*, H.L. Thronson, J.M. Shull (eds.) (Kluwer: Dordrecht) p.493.
- Rohlfs, K., Kreitschmann, J., Siegman, B., Feitzinger, J.V. (1984), *Astr. Ap.* **137**, 343.
- Schwering, P.B.W. (1988), PhD. Thesis, Leiden University (NL).
- Schwering, P.B.W., Israel, F.P. (1990), *Atlas and Catalogue of Infrared Sources in the Magellanic Clouds* (Kluwer: Dordrecht).