Carbon Monoxyde in the Magellanic Clouds

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1. The Results Achieved with SEST and Future Perspectives

Thanks to the good angular resolution of the SEST, much progress has been done on the properties of molecular gas in the Magellanic Clouds, and this is outlined in the following sections. A substantial fraction of the Clouds has been mapped in the CO lines at a linear resolution of about 10 pc, sufficient to resolve the ordinary molecular clouds inside large gas complexes. Multi-line observations have allowed to explain why these clouds look different in CO than Galactic clouds: this is due to a combination of lower heavy-element and dust abundances and of a higher far-UV flux (and probably MeV-energy cosmic ray flux) in the Magellanic Clouds. However, many observations of faint lines were done with poor signal/noise ratios and should be redone with the new receivers. We still do not know accurately how much molecular gas (essentially H_2) there is in the Clouds. In their inner regions, molecular gas is undoubtedly less abundant than atomic (H I) gas, but this might not be true in the outer regions. More work is required to obtain better estimates of the amount of H_2. This will be done by far-UV observations of H_2 absorption lines in front of a number of Magellanic Cloud stars with the FUSE satellite to be launched late this year. Information on the H_2 content of the molecular clouds themselves should come indirectly from observations of the dust emission at 200 µm presently in progress with ISO, and mainly from observations of this emission at millimetre and submillimetre wavelengths to be performed with the bolometers of the SEST. On the longer term, the LSA/MMA should provide very high-resolution maps of molecular clouds in the CO and other molecular lines as well as in the dust continuum emission: this will open entirely new windows on the physics of the interstellar clouds and of star formation in conditions very different from what can be found in our Galaxy.

2. The Main Goals of CO Observations in the Magellanic Clouds

The Magellanic Clouds are less evolved than our Galaxy. Less interstellar matter has been processed into stars, and they still contain a considerably larger fraction of gas (about 10% of the total mass for the LMC and perhaps one half for the SMC, considering only the atomic gas). Also, the abundances of heavy elements in stars as well as in the interstellar matter are quite smaller (about 1/2.5 and 1/10 of the Solar abundances for the LMC and the SMC respectively). Still, both Clouds presently form stars at a higher rate than our Galaxy, about 10 times per unit area on average that in the Solar neighbourhood. They contain a considerable number of luminous, hot young stars, in particular in giant active regions like 30 Dor in the LMC or N 66 in the SMC, for which there is no equivalent in the Milky Way. These stars emit a large flux of far-UV photons which heats and partly ionises the interstellar gas. All this leads us to expect that the interstellar matter in the Magellanic Clouds should exhibit rather unusual properties. Understanding these properties will help us to understand what happens to interstellar gas in even more extreme situations like those in starburst galaxies or in galaxies at very high redshifts.

In spite of this, relatively little has been done until recently on the study of the interstellar gas in the Magellanic Clouds. This was mainly due to the lack of suitable instruments in the Southern Hemisphere. For example, no sensitive interferometer able to observe the 21-cm line of atomic hydrogen was available before the Australia Telescope Compact Array, and all the previous H I work was done with the 64-m Parkes telescope at the relatively poor angular resolution of 14 arc minutes, corresponding to 200 pc at the distance of the LMC. This situation is rapidly improving: a 21-cm line map of the SMC has just been published with a resolution of 28 pc (Staveley-Smith et al., 1997, *MNRAS* 289, 225), and a similar work is in progress for the LMC. The situation for the molecular gas is comparable: after a single detection of CO in 1975 and a limited CO survey using the ESO 3.6-m telescope equipped with a millimetre receiver (Israel et al., 1986, *ApJ* 303, 186), the 1-m "mini-telescope" of Columbia-Harvard located at Cerro Tololo was used to produce low-resolution (9 arc minutes or about 150 pc) maps of the LMC, then of the SMC in the $^{12}CO(1-0)$ line at 2.6 mm wavelength (Cohen et al. 1988, *ApJ* 331, L95; Rubio et al., 1991, *ApJ* 368, 173). It is only with the availability of the 15-m diameter Swedish-ESO Submillimetre Telescope (SEST) at La Silla that relatively high-resolution CO line mapping has become possible.

The main goal of the CO observations of the Magellanic Clouds is clearly

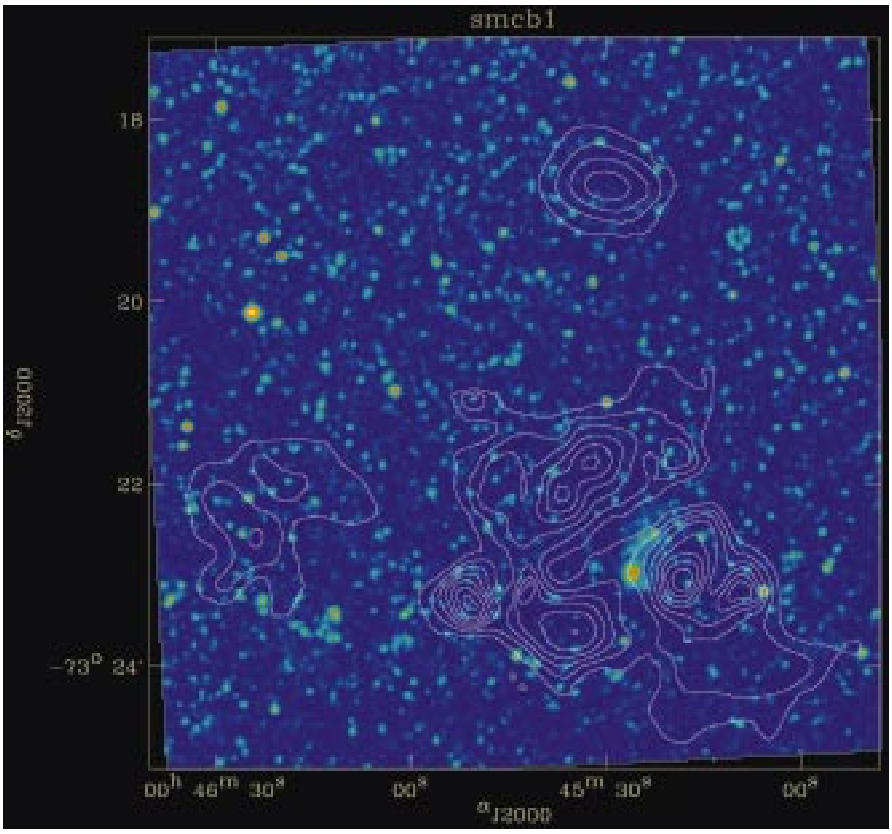

Figure 1: A molecular complex in a region to the south-west of the SMC (SMC-B1), as seen with the SEST in the $^{12}CO(1-0)$ line, overlaid on the Digital Sky Survey image. There are a few faint H II regions in this area, one of which is visible at the middle of the molecular complex at the bottom right. The cloud to the top is not associated with an H II region, but contains an embedded new-born star.

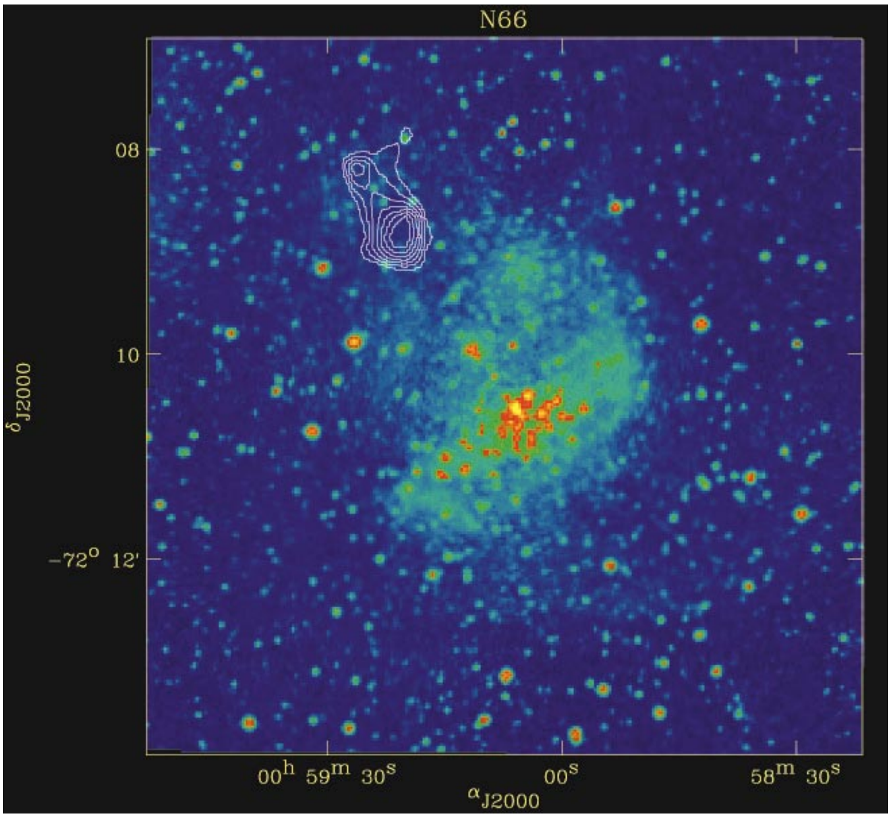

Figure 2: The only surviving molecular cloud in the region of N 66 in the SMC. The contours correspond to the emission in the $^{12}CO(2\text{-}1)$ line, overlaid on the Digital Sky Survey image where the H II region can be seen as a diffuse emission, with the ionising star cluster at the centre.

to look for the molecular component of the interstellar matter. Stars are formed in dense, molecular clouds and the active star formation in the Magellanic Clouds suggests that this molecular component should be present, and perhaps abundant. Of course, molecular hydrogen is the main constituent of molecular clouds but direct observation of its emission is almost impossible unless it is highly excited by some process: one has to rely on other, rarer molecules to trace the molecular gas. CO is the easiest to observe and perhaps also the most interesting of these molecules, but there are others like OH, CS, HCO^+, HCN, HNC, etc. which have also been observed in the Magellanic Clouds, mostly with the SEST. I will not discuss the latter molecules, and will concentrate on CO. I will first describe the present status of the CO observations, and then show how they have been used to derive some physical properties of the molecular clouds. I will also attempt to answer the difficult question of the amount of molecular hydrogen in the Magellanic Clouds as derived from CO line observations.

3. The CO ESO-SEST Key Programme

Most of the CO observations in the Magellanic Clouds have been done in the framework of the CO ESO-SEST Key Programme, by a consortium of astronomers from the Observatories of Leiden, Onsala, Paris, ESO-La Silla, of SRON in Groningen, of the Universities of Chile, of the Rensselaer Polytechnic Institute in Troy (NY, USA), and a few others. A large amount of telescope time at the SEST has been devoted to this programme, shared equally between ESO and Sweden. The programme was entirely done using the first-generation of receivers. This is somewhat unfortunate: it would have been completed much more rapidly with the new, excellent receivers. The first observations consisted in a survey of the $^{12}CO(1\text{-}0)$ line at 2.6 mm in the direction of the main far-infrared peaks mapped with IRAS in the Clouds. Most of them were detected, but the emission was found to be weaker than in comparable Galactic regions by an average factor of 3 in the LMC and 10 in the SMC. The corresponding line of the ^{13}CO isotopic molecule was also observed in the brightest CO sources: the $^{12}CO(1\text{-}0)/^{13}CO(1\text{-}0)$ line intensity ratio was found to be 2–3 times larger than in our Galaxy. These results have been published by Israel et al. (1993: Paper I).

The next step was to map molecular cloud complexes. Their approximate location was already known through the 1-m mini-telescope observations cited above. The selected regions were systematically explored with increasingly finer position grids, in order first to detect the CO-emitting regions, then to map them with the full 43″ (about 10 pc) resolution of the SEST. In the SMC we concentrated on several fields in the active star-forming region at the southwest of the main body (Fig. 1), but some CO clouds in other active and quiet places were also included. In particular, a large area around N 66, the main H II region in the SMC, was surveyed but only a single molecular cloud was found to have survived the harsh conditions there (Fig. 2). Many regions have also been observed in the $^{12}CO(2\text{-}l)$ line at 1.3 mm and some in the lines of $^{12}CO(3\text{-}2)$ at 0.85 mm, and in lines of ^{13}CO. Most of these results have been published by Rubio et al. (1993a: Paper II; 1996: Paper V).

A large body of similar observations has also been obtained in the LMC. They concern mainly the region of 30 Dor (Fig. 3), large areas south of it, and the star-formation complex around N 11 at the north-west of the Cloud. Like in N 66, little CO has survived in the region of 30 Dor. Near-IR observations have shown that limited star formation is taking place in the remaining clouds. Only a part of the LMC observations has been published as yet, by Kutner et al. (1997: Paper VI) and by Johansson et al. (1998: Paper VII). A study of the region of N 4 made independently of the Consortium has been published by Heydari-Malayeri & Lecavelier des Etangs (1994, *A&A* 291, 960). We will now discuss the interpretation of these results.

4. The Formation of the CO Lines and the Properties of the Molecular Clouds

Like in our Galaxy, the ^{12}CO lines are almost always optically thick in the Magellanic Clouds, as it can be seen immediately from the low $^{12}CO(1\text{-}0)/^{13}CO(1\text{-}0)$ line intensity ratios: they are considerably lower than the expected abundance ratio of the respective molecules which should be close to the $^{12}C/^{13}C$ isotopic ratio (about 70 in our Galaxy and probably more in the Magellanic Clouds). Due to the optical thickness of the ^{12}CO line the observed emission in this line comes only from the surface of the molecular clouds while the optically thin lines of the rarer isotopic molecules ^{13}CO or $C^{18}O$ come from deeper regions and can tell us something about the inside of the clouds. The $^{12}CO(2\text{-}1)/^{12}CO(1\text{-}0)$ line intensity ratios of 1.0 or slightly more that are measured in the SMC and LMC clouds imply that the emitting regions are relatively dense and warm, with a kinetic temperature of at least 10 K: the ratios would be smaller otherwise due to a lower population of the J = 2 level of the CO molecule compared to that of the two lower levels (J = 1 and 0). These relatively high temperatures (compared to those in our Galaxy) are confirmed by the high ^{13}C)(2-1)/^{13}CO(1-0) line intensity ratios, which indicate that the inner regions of the clouds are also warm. More accurate values can be derived from multi-line modelling (see Johansson et al., 1997: Paper VII). Then we expect to measure a brightness at the centre of the ^{12}CO(1-0) or of the ^{12}CO(2-1) line roughly equal to that of a blackbody at 10 K, or more. The observed brightnesses are considerably smaller. This can be explained if the emitting regions cover only a part of the beam of the radio telescope: in other words, the molecular clouds are clumpy and only the clumps emit. Then the average brightness measured by the radio telescope is equal to that of a blackbody at 10 K (or somewhat higher) multiplied by the surface filling factor of the clumps. We find that this filling factor is of the order of 0.1 in the SMC, and probably somewhat closer to unity in the LMC. This contrasts very much with what we normally see in our Galaxy where the brightness of the clouds in the CO lines is not very different from what is expected from independent determinations of their temperature, the filling factor of the emitting regions being then close to unity. This apparent difference in the structure of the clouds explains the paradoxical observation that the molecular clouds in the SMC and LMC emit less in CO than the Galactic ones while being warmer. Details on the preceding reasoning can be found in Rubio et al., 1993b (Paper III).

In order to proceed further, we have compared the observations to the results of models. Molecular clouds are generally immersed in a far-UV radiation field which photodissociates CO and other molecules like H_2 at the surface of the cloud. The UV radiation field also heats up the gas in the outer regions of the cloud. The combined effect of this heating, of photodissociation and of the ^{12}CO line optical depth is such that the ^{12}CO(1-0) line (as well as the ^{12}CO(2-1) one) is efficiently emitted only in a thin layer. Appropriate self-consistent models of photodissociation regions including chemistry, thermal balance and radiative transfer (in particular in the photodissociating far-UV lines of CO and H_2) have been built by Lequeux et al. (Paper IV). They assumed conditions which are considered to be typical of the SMC: a far-UV radiation field 10 times higher than in our Galaxy in the Solar neighbourhood, and a flux of low-energy cosmic rays also 10 times higher: these MeV particles are probably accelerated in supernova remnants and interstellar bubbles and contribute to the heating of the interstellar matter, especially inside the clouds. Also, the abundances of heavy elements were taken to be 10 times smaller than in our Galaxy, as well as the abundance of dust which however absorbs relatively more in the far-UV than Galactic dust. As expected, these models predict the brightness of the SMC photodissociation regions in the ^{12}CO lines to be significantly higher than in our Galaxy. However, if we consider a cloud with a range of densities it is clear that CO (and H_2) are destroyed preferentially in lower-density regions where the UV radiation penetrates more

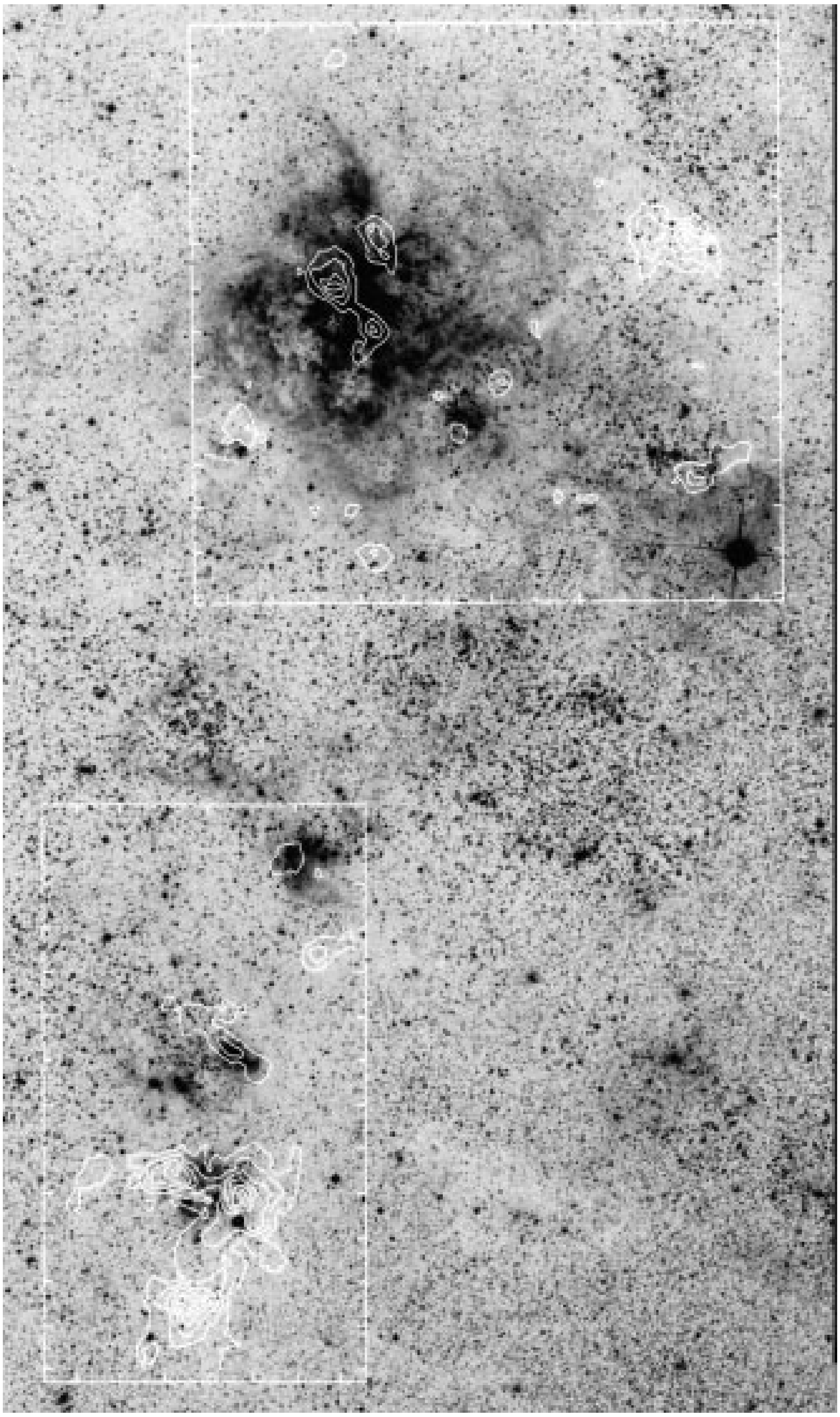

*Figure 3: Molecular clouds in two fields of the LMC fully surveyed in the ^{12}CO(1-0) line (rectangles). The CO emission corresponds to the contours, overlaid on a SERC blue Schmidt plate. North is at the top, east to the left. Tickmarks at 2′ spacings are shown. The northern field contains the 30 Doradus region, and the southern field the H II regions N 158C, N 160 and N 159, from north to south. Only a few molecular clouds have survived near 30 Dor. Note the isolated cloud south of N 159. It has different properties from the two clouds directly associated with the H II region: it is colder, and shows no emission in the 158 µm line of [C II] contrary to the two other clouds (Israel et al., 1996, ApJ **465**, 738). From Johansson et al., A&A in press.*

easily. Formation of both molecules is also slower at low densities. Thus CO (and to a lesser extent H_2 which is more resistant to photodissociation) survives only in relatively high-density regions (the clumps) while the lower density ones (the interclump medium) are fully photodissociated. In our Galaxy, the average UV flux is lower, CO is more abundant due to the higher abundance of carbon, and dust which absorbs the far-UV radiation is also more abundant. In consequence, CO can survive in relatively low-density regions, so that most of the volume of the cloud emits and its apparent surface brightness in the ^{12}CO lines is much more uniform. This explains physically the difference between Galactic and SMC clouds. In fact it is now well known that interstellar matter in our Galaxy, including molecular clouds, has a very non-uniform, hierarchical and perhaps fractal structure; there is no reason why the Magellanic Clouds should behave differently in this respect. Of course our clump-interclump model is not an accurate representation of reality, but it allows to understand qualitatively what happens.

5. The Mass of Molecular Gas in the Magellanic Clouds

Now that we understand better the physics of molecular clouds in the Magellanic Clouds, we can try to estimate from the intensity of the $^{12}CO(1\text{-}0)$ line how much molecular gas (essentially H_2) there is in the Magellanic Clouds. In other words, the problem is to determine the quantity $X = N(H_2)/I(CO)$ which relates the column density of molecular hydrogen $N(H_2)$ to the brightness in the $^{12}CO(1\text{-}0)$ line I(CO). This is a noteworthy difficult problem even in our Galaxy, due to the impossibility to estimate directly the amount of H_2. The best recent determinations for our Galaxy converge to values of X in the range 1–2 10^{20} mol. cm^{-2} (K km $s^{-1})^{-1}$. They are based on gamma-ray results from COS-B or EGRET (Strong & Mattox, 1996, *A&A* 308, L21) or on studies of the millimetre continuum emission of dust in spiral galaxies similar to ours (Dumke et al., 1997, *A&A* 325, 124). None of these two methods can be applied to the Magellanic Clouds for the time being. However, a possible way to estimate X there is to assume that the molecular clouds are in virial equilibrium, allowing to derive their total mass. *If this mass is assumed to be made mainly of* H_2 (with some correction for helium), it is easy to derive a mean column density of H_2 in the beam of the radio telescope with which the CO observations are made, and to calculate X. This was first attempted on the large complexes detected with the 1-m mini-radio telescope, with the result that X is considerably larger than in our Galaxy (respectively by a factor 6 and 20 for the LMC and the SMC). However this result is questionable because it is not at all certain that these big complexes, 200 pc or so in size, are in virial equilibrium; moreover, atomic hydrogen, which contributes to the virial mass, cannot be neglected at this scale with respect to H_2 due to the very efficient photodissociation of H_2. At the smallest scales that are accessible to the SEST (10 pc), Rubio et al. (1993b, Paper III) find $X \simeq 9\ 10^{20}$ mol. cm^{-2} (K km $s^{-1})^{-1}$ for the SMC, 4–8 times higher than in our Galaxy, while X may be 2 times higher in the LMC than in our Galaxy. The assumption of virial equilibrium is perhaps more reasonable for such small clouds than for large gas complexes in which forces other than self-gravity might dominate. Still, there is the problem that even in 10 pc clouds the gas is only partly molecular due to photodissociation of molecules, in particular CO, in the low-density parts: although as I have said earlier H_2 is more robust than CO against photodissociation due to more efficient self-shielding in the photodissociating far-UV lines, it might well be dissociated too. It is difficult to estimate how much H I exists in the clouds but in any case the above values of X should be considered as upper limits. If we take them at face value, there is a maximum of $10^7\ M_\odot$ of H_2 in the SMC (2% of the total gas content), and of $5\ 10^7\ M_\odot$ in the LMC, implying a molecular/atomic gas mass ratio of at most 10%.

Recently, Israel (1997, *A&A* 328, 471) proposed another method to estimate X, which gives different results. It rests on the comparison of H I, CO and far-infrared maps. The basic assumption is that dust, which emits in the far-IR, is well mixed with the gas; in regions far from molecular complexes, the far-IR/21-cm line intensity ratio is proportional to the dust/gas ratio. In the molecular complexes, the far-IR/21-cm ratio is considerably larger. This is due to the far-IR emission of the dust associated with molecular gas, and also to a higher dust temperature since these regions are also in general regions of active star formation, thus of high radiation field which heats the dust. If one corrects for the effect of the higher dust temperature, then one can obtain the amount of molecular gas independently of CO observations. One can then calculate X. Israel uses the observed 60 μm/100 μm intensity ratio from IRAS to estimate the temperature of the dust and its far-IR emission. Unfortunately, this method depends implicitly on assumptions about the nature of the dust (which is known to have different properties than Galactic dust), and the far-IR brightness is extremely sensitive to the dust temperature. The values of the column densities of H_2 and of X derived in this way are extremely high, of the order of $X = 13\ 10^{20}$ mol. cm^{-2} (K km $s^{-1})^{-1}$ for the LMC and 120 10^{20} mol. cm-2 (K km s-l)$^{-1}$ for the SMC, at scales of about 200 pc. Using the millimetre emission of the dust, which is only linearly sensitive to temperature, instead of its far-IR emission, would give considerably safer results. This is the method used by Guélin and associates (Dumke et al., 1997, *A&A* 325, 124 and references herein) for a number of edge-on spiral galaxies, but millimetre data are still lacking in the Magellanic Clouds.

H_2 might also exist in regions far from the large star-formation complexes, even in the absence of CO emission. In the inner regions of the Clouds however the existence of a lot of H_2 is unlikely simply because extinction is generally small and there is far-UV radiation everywhere, as can be seen directly on UV images of the Clouds. Amongst 5 stars observed in the far-UV in each of the Magellanic Clouds, only the one with the largest amount of interstellar extinction (A_V=0.75) shows H_2 absorption on its line of sight (Walborn et al., 1995, *ApJ* 454, L27). Stars with such a high extinction are rare in the Clouds except in the region of 30 Dor. Large amounts of cold H_2 might however exist in regions shielded from far-UV radiation, for example in the outermost regions of the Clouds. Lequeux (1994, *A&A* 287, 368) proposed that there might be a lot of H_2 in the external regions of SMC for which counts of background galaxies apparently show regions of extinction with no correspondence in atomic hydrogen. This should be confirmed, however. Knut Olsen and Paul Hodge are currently working on the problem using deeper galaxy counts and colours from HST images, which are less subject to spatial fluctuations due to clusters of galaxies or to the large-scale structure of the Universe (see Olsen & Hodge, 1996, *BAAS* 188, 61.13).

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