THE ESO/SEST KEY PROGRAMME: CO IN THE MAGELLANIC CLOUDS

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1. Introduction

The ESO SEST Key Programme was established to investigate molecular gas in the Magellanic Clouds. These galaxies provide a unique opportunity for studying molecular clouds and star formation in galaxies whose environment is different from that of the Milky Way. In the LMC, the gas-to-dust ratio is 4 times higher than in our Galaxy (Koorneef 1982) and the metal abundance is about 4 times lower (Dufour 1984). In the SMC, these values are even larger, ~17 times larger than our Galaxy for the gas-to-dust ratio and a metal abundance of about 10 times smaller (Dufour 1984, Koorneef 1984). Because of their proximity, 50 kpc for the LMC and 63 kpc for the SMC, the SEST telescope with an angular resolution of $43''$ at 2.6 mm provides a linear resolution of 10 pc at the LMC distance, well suited for resolving the largest molecular clouds. The main goals of this programme were to determine the physical properties of the molecular gas in the Magellanic Clouds, derive the characteristics of the CO clouds and compare them to those of the Giant Molecular Clouds (GMC) found in our Galaxy, and to address the question of the conversion of CO luminosity, $L_{\rm CO}$, to molecular hydrogen mass, $M({\rm H_2})$, in an environment with dust content and metal abundance different to that of the Milky Way. In this contribution we summarize the results of this programme which started in May 1988 and ended in January 1995. Detailed results are being presented as a series of publications in *Astronomy and Astrophysics.* Further details and goals of the programme can be found in Israel et al. (1993; Paper I).

2. Observations

The observations were made during several runs with the Swedish-ESO Submillimeter Telescope (SEST). This radiotelescope is located at La Silla Observatory (Chile) and has a diameter of 15 m; it has beams (FWHM) of $43''$ and $22''$ at the $CO(1 \rightarrow 0)$ and $CO(2 \rightarrow 1)$ frequencies, respectively. The backend is an acousto-optical spectrometer with a total bandwidth of 86 MHz and a channel width of 0.043 MHz, corresponding to a velocity range of 230 km s^{-1} and a velocity resolution of 0.11 km s^{-1} at $CO(1 \rightarrow 0)$ and 112 and 0.056 km s^{-1} at $CO(2 \rightarrow 1)$, respectively. Observations were done in frequency-switch mode with a throw of 15 MHz for $^{12}CO(1 \rightarrow 0)$, and position-switch mode, with a reference position far from the known CO emission zones, for the three other lines. The system temperature varied between 400 and 800 K for $CO(1 \rightarrow 0)$ and 900 to 1500 K for $CO(2 \rightarrow 1)$. The integration time at each position was automatically varied in order to secure a uniform noise level; in general, 0.1 K per channel at all frequencies. Telescope pointing was checked on the strong SiO maser R Dor, and calibration spectra were done on the strongest lines in the LMC (N159) and SMC (LIRS 49). We estimate the maximum pointing errors as about $5''$. The calibration used the usual absorbing chopping wheel method, and observations of blackbodies at two temperatures. The antenna temperature scale was checked sporadically on the cloud OMC1.

3. The Small Magellanic Cloud

In the SMC, observations in the $^{12}CO(1 \rightarrow 0)$line toward the central region of the southwest part of the Bar and some selected HII regions were performed (see Fig. 1 of Rubio 1992). About a dozen molecular clouds were identified and fully mapped in $^{12}CO(1 \rightarrow 0)$ (Rubio et al. 1993a, Paper II; Rubio et al. 1996, Paper V). The CO clouds have sizes ranging from 10 to 20 pc, line widths between 1.6 and 4.9 km s^{-1} , CO luminosities between 0.5×10^3 to 6.4×10^3 $L_\odot$, and virial masses ranging from 2 to 9×10^4 $M_\odot$. The characteristics of the CO clouds in the SMC are different from those of galactic GMCs. They have smaller sizes and are less luminous in CO than galactic GMCs. From the excitation temperatures derived from the modelling of observed line ratios (Lequeux et al. 1994, Paper IV) and the observed antenna temperatures, it is found that the SMC CO clouds are clumpy with filling factors smaller than that of Galactic CO clouds. The relationships between $L_{\rm CO}$and Δv and $L_{\rm CO}$vs. $M_{\rm vir}$ for SMC-CO clouds are noticeably different from those of Galactic molecular clouds. At the scales resolved by SEST (10pc), the CO clouds are less luminous by a factor of 2 compared to outer galaxy clouds and at the largest scales (200pc) this factor increases to 10 (Rubio et al. 1993b, Paper III). These differences can be explained by the combined effects of a higher UV radiation field and of a lower abundance of heavy elements and of dust which produces a higher rate of photodissociation of CO (Maloney & Black 1988, Elmegreen 1989). In the SMC contrary to our Galaxy, CO can only survive in dense clumps while it is completely photodissociated in the diffuse medium. Presumably most of the interstellar medium in the SMC is atomic rather than molecular.

To determine the physical properties of the SMC molecular clouds, observations at the peak position of six molecular clouds in four CO lines [^{12}CO($1 \rightarrow 0$), ^{13}CO($1 \rightarrow 0$), ^{12}CO($2 \rightarrow 1$), and ^{13}CO($2 \rightarrow 1$)] with the same angular resolution were performed. The derived line ratios range from 7 to 25 for ^{12}CO($1 \rightarrow 0$)/^{13}CO($1 \rightarrow 0$); from 0.8 to 1.3 for ^{12}CO($2 \rightarrow 1$)/ ^{12}CO($1 \rightarrow 0$), and from 1.0 to 2.7 for ^{13}CO($2 \rightarrow 1$)/^{13}CO($1 \rightarrow 0$). The six clouds under consideration can be classified into 3 categories: i) the "hot" clouds, N 88 and N 66 (Henize 1956), which are close to bright HII regions and exhibit large ^{13}CO($2 \rightarrow 1$)/^{13}CO($1 \rightarrow 0$) integrated line intensity ratios; ii) the "warm" clouds, LIRS 49 and LIRS 36 (Schwering & Israel 1989), which are close to less bright HII regions and exhibit smaller ^{13}CO($2 \rightarrow 1$)/^{13}CO($1 \rightarrow 0$) ratios; and iii) the "cold" clouds, SMC-B1#1 (Paper II) and Hodge 15 (Hodge 1984), which are far from HII regions and have low ^{13}CO($2 \rightarrow 1$)/^{13}CO($1 \rightarrow 0$) ratios. These line ratios have been compared with the predictions of a one-side illuminated plane-parallel model which treats consistently radiative, chemical and excitation processes of CO and its isotopes in SMC conditions (Lequeux et al. 1994, Paper IV). The observed line ratios are consistent with models in which the molecular gas has a moderately high density ($10^4 - 10^5$ cm^{-3}). The model shows that gas at low densities, (say $n(\mathrm{H_2}) = 100$ cm^{-3}) is completely photodissociated in the SMC and contains no CO, nor even H_2 in extreme cases. This study confirms the conclusions of Rubio et al. (1993b, Paper III): i) that the high observed ^{13}CO($2 \rightarrow 1$)/^{13}CO($1 \rightarrow 0$) ratios imply high excitation temperatures of the emitting gas; and ii) that the surface filling factors of the emission are low (eg., a value of $\sim$0.08 was derived for the hot clouds).

4. The Large Magellanic Cloud

In the LMC, observations in the ^{12}CO($1 \rightarrow 0$) line towards 92 IRAS sources were first reported by Israel et al (1993). During the following observing periods of the Key programme, several regions were fully mapped in the ^{12}CO($1 \rightarrow 0$) line. These are: a) 30 Dor and N159 regions (Booth 1991; Johansson 1991; Johansson; Booth & Heikkila 1995); b) N11 region (de Graauw et al. 1996; Kutner & Rubio 1996); c) 30 Doradus Central and Southern Complex (Kutner & Rubio 1996; Kutner et al. 1996); and d)

Cloud 37 (Garay et al. 1996). A total of 86 molecular clouds have been identified. The LMC CO clouds have sizes ranging from 10 to 40 pc, line widths between 2.5 and 10 km s^{-1} , CO luminosities between 8×10^2 to 1.3×10^4 K $km\ s^{-1}\ pc^2$, and virial masses ranging from 10^3 to 7×10^5 M$_\odot$. These clouds, although larger in size and more massive than those found in the SMC, do not look like typical GMCs in the Galaxy. Their characteristics are closer to molecular clouds in the outer Galaxy than in the inner Galaxy (see Figures 1 and 2). The line width versus size relationship, for the clouds within the N11, Cloud 37, 30 Doradus Central, and 30 Doradus Southern regions, follow the power law relation $\Delta v = (6.5 \pm 1.4)\ R^{0.5\pm0.1}$. The slope is similar to that of molecular clouds in our Galaxy and also to the slope of SMC clouds. The Δv vs. $L_{\rm CO}$and $L_{\rm CO}$vs. $M_{\rm vir}$ relationships are different from those found for Galactic molecular clouds. A linear fit to the $L_{\rm CO}$versus Δv relation for the same ensemble of LMC clouds gives $L_{\rm CO}$= $(170 \pm 3)\Delta v^{1.8\pm0.3}$. A linear fit to the CO luminosity versus virial mass for the LMC clouds gives $M_{\rm vir} = (155 \pm 2)\ L_{\rm CO}^{0.78\pm0.07}$.

5. Comparison to Galactic Molecular Clouds

In this section, we briefly discuss a comparison of the properties of the molecular clouds in the LMC and SMC with those in our Galaxy. As representatives of the latter, we have used recent data of southern hemisphere clouds obtained with the 1.2 m Columbia telescope at CTIO. May et al. (1996) reported the characteristics of 187 molecular clouds in the III Quadrant of our Galaxy. We also used the data of 75 molecular clouds identified in the inner IV Quadrant of the Galaxy (Bronfman, private communication).

Figure 1 shows the $L_{\rm CO}$versus Δv relationship for LMC, SMC, and Galactic clouds. Molecular clouds in the Magellanic Clouds appear to be less luminous in CO than molecular clouds in the outer Galaxy in a given range of line widths. Note that, in that plot, inner Galaxy CO clouds concentrate in the range of large line widths where only a few Magellanic Cloud clouds are found, these being much less luminous in CO than their galactic counterparts.

In Figure 2 we plot the ratio $X/X_{\rm gal}$ as a function of R, where $X_{\rm gal} = 2.3 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$. The factor X is defined such that $X = M({\rm H_2})/L_{\rm CO}$. To compute the X factor for molecular clouds we used as mass their virial mass, $M_{\rm vir} = 190\ R\Delta v^2$. The points in this figure show a large spread but some trends are evident. Inner Galaxy clouds tend to concentrate around the canonical value for the Galaxy, $X_{\rm gal}$, determined from other methods (Strong et al. 1988). That is, for inner galactic clouds $X/X_{\rm gal} \approx 1$. Outer Galaxy clouds exhibit a larger spread, but with an

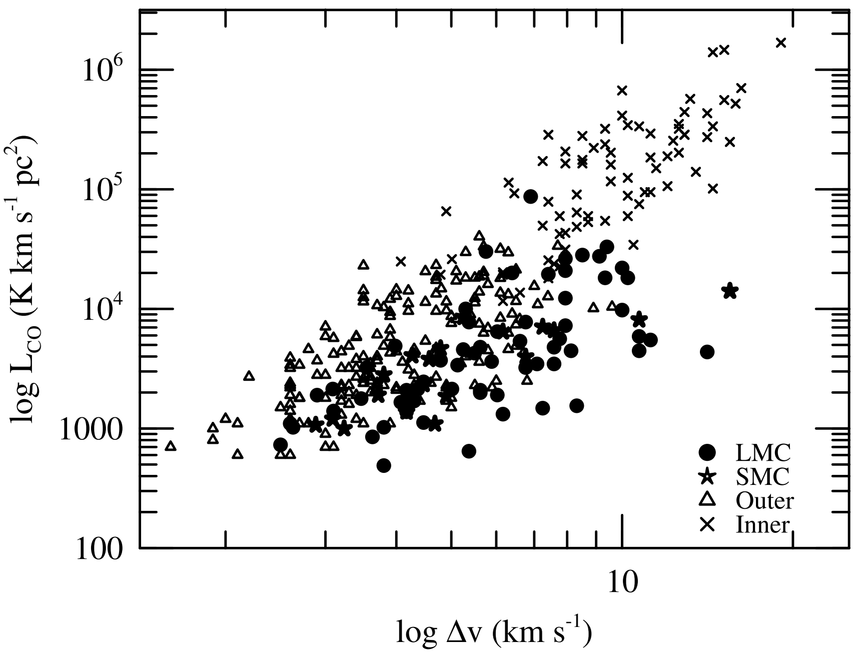

Figure 1. CO luminosity versus line width for molecular clouds in the LMC (black dots), SMC (black stars), outer Galaxy (open triangles) and inner Galaxy(crosses).

average value of $\log[X/X_{\rm gal}] = 0.4$, indicating that the conversion factor is about 2.5 times larger than the Galactic value (May et al. 1996). For SMC clouds, Rubio et al. (1993b) found that $X_{\rm SMC}$ is larger than the Galactic value, and that in addition this factor depends on the scale size, $X_{\rm SMC}/X_{\rm gal} = 3.9(R/10{\rm pc})$.

CO clouds in the LMC and SMC cover a similar range of sizes as outer Galaxy clouds, while exhibiting larger values of X, with an average value of about 4 times larger than the canonical Galactic value. Johansson (1991) found an X value for the 30 Doradus clouds of about two times larger than the Galactic value, and Israel and de Graauw (1991) found an X value of three times the Galactic one for the N11 clouds. The spread of the X values in the Magellanic Clouds is about one order of magnitude. An explanation of this result would require investigation into the dependence of X on the local ambient conditions of the molecular clouds. LMC and SMC molecular clouds seem to share similar properties. In both Figures 1 and 2, no appreciable difference is seen between LMC and SMC clouds. They follow the same CO luminosity-line width relationship and are indistinguishable in the

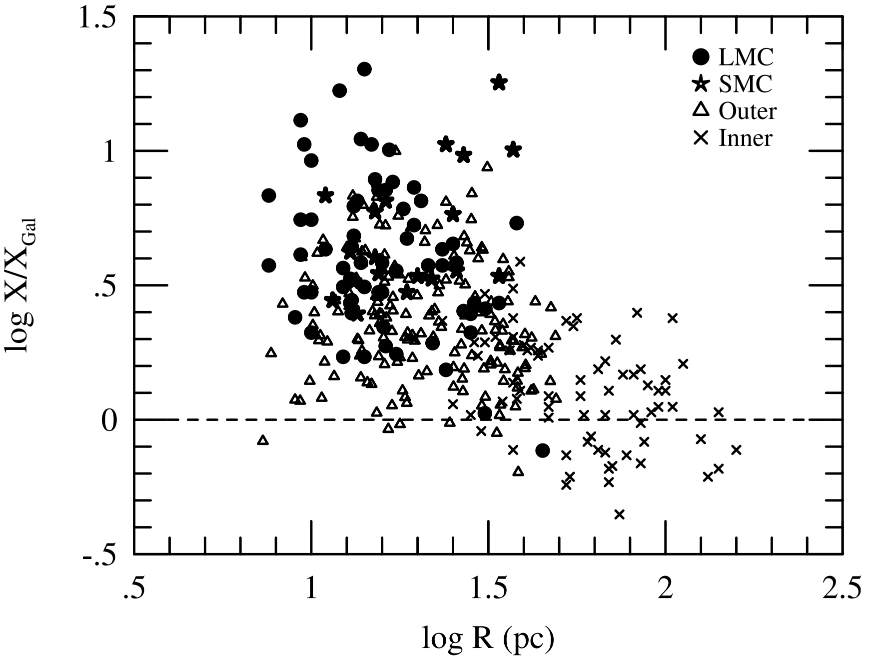

Figure 2. Ratio of the conversion factor X/X_{gal} for molecular clouds in the LMC (black dots), SMC (black stars), outer Galaxy (open triangles) and inner Galaxy (crosses) versus size.

conversion factor versus size dependence (see Figure 2). Clearly, more work is needed to determine how local ambient conditions, e.g, photodissociation, metallicity, etc, affect the properties of the CO clouds. The suggestion that the conversion factor depends linearly on metallicity (Cohen at al. 1988) or that the X factor decreases with metallicity (Rubio et al. 1991, Verter & Hodge 1995) is not as straightforward as proposed. This result is currently being investigated and will be one of the main outcomes of this long term project.

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