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Molecular Line Observations in the Magellanic Clouds

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Abstract. We review the present knowledge of molecular line studies and its relation to interstellar medium properties in the Large and Small Magellanic Clouds. The physical and chemical properties of the molecular gas together with the abundance of different molecular species will be discussed.

1. Introduction

The Large and Small Magellanic Clouds (LMC, SMC), the two nearest extragalactic systems of well known distance, provide a unique opportunity to study physical processes in an interstellar medium different to that of our Galaxy. They have a lower metallicity, higher gas to dust ratios and strong UV radiation fields, and constitute the best target for a detailed study of the molecular gas content, its properties, and the process of star formation. In fact, they are the nearest metal-poor systems with active star formation ($Z_{lmc} \sim Z_{\odot}/4$ and $Z_{smc} \sim Z_{\odot}/9$, Kurtz and Dufour 1998) and thus, are the most appropriate systems where the physics and chemistry of the interstellar medium (ISM) can be investigated.

2. Observations

Simultaneous observations in CO(2-1) and CO(1-0) and isotopomers were possible at the SEST telescope after the SIS receivers were installed in 1996.

A deep CO(2-1) survey of molecular regions in the LMC and SMC was performed as an ESO Large Programme (Rubio 2003). These observations were done during 2000-2002 with the SEST telescope and covered a selected number of molecular clouds from the ESO-SEST KEY PROGRAMME (Israel et al. 1993). The clouds were fully sampled at 10" spacing with an rms of 0.01 K. The observations included 30 Doradus, 30 Dor Complex, N11, in the LMC and all of the SMC CO clouds detected in CO(1-0). Specific programs towards N159 in the LMC and N83/N84 in the SMC had been done by Bolatto et al. (2001) and Bolatto et al. (2003), respectively. The LMC arc east of the 30 Doradus complex was also observed (Mizuno, Johansson, private communication). Observations of the ^{13}CO(2-1) and ^{13}CO(1-0) lines heve been done towards the center of the strongest CO clouds mapped at ^{12}CO(2-1). Previously, Chin et al. (1996; 1997) performed ^{13}CO observations towards LIRS36 in the SMC and N113 in the LMC.

The strongest CO clouds, N159 in the LMC and LIRS49 (N27) have been used as targets for multi-line studies. HCO^+ , HCN, CS, HNC, $C^{18}O$, H_2CO

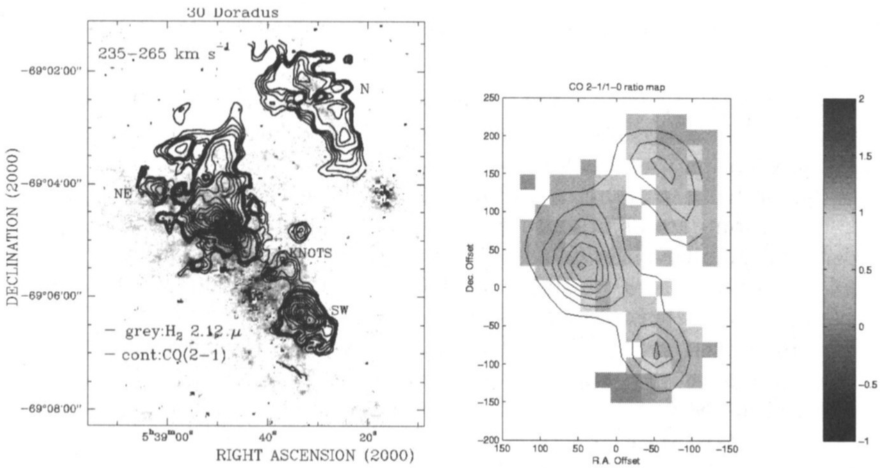

Figure 1. (a)Velocity integrated CO(2-1) emission of the 30 Doradus region. (b) CO(2-1)/CO(1-0) ratio over the region.

were detected (eg. Heikkila et al. 1998, 1999; Chin et al. 1996, 1997, 1998; Johansson et al. 1994).

3. Results

The characteristics of the molecular clouds and their physical properties are given in the following.

3.1. Properties of Molecular Clouds

Properties of the molecular clouds have been determined from the CO(1-0) surveys done with different resolutions in the Magellanic Clouds. The ESO SEST Key program has produced a wealth of CO data. About 150 molecular clouds have been fully mapped. These clouds are resolved at the 45 arcsec resolution ($\sim$ 20 pc) of the observations. The LMC molecular clouds show the following properties. The 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}, 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 (Rubio 1996). They are under-luminous in CO while they show virial masses typical of those of Galactic GMCs. Many of the clouds associated with HII regions are smaller in size than the ionized region, contrary to what is found in our Galaxy (Israel et al. 2003, and references therein).

In the Small Magellanic Cloud (SMC) the CO clouds show properties which are significantly different to those of galactic molecular clouds. They are smaller in size, less luminous in CO and less massive. No diffuse CO emission has been detected and the relation between the intensity of the CO emission and the molecular hydrogen column density is larger than the factor derived from molecular clouds in our Galaxy and dependent on cloud size (Israel et al. 1993; Rubio et al. 1993; Rubio, Lequeux, & Boulanger 1993).

3.2. The Physical Properties of Molecular Clouds: The CO(2-1/1-0) Ratio

1. 30 Doradus: Figure 1(a) shows the velocity integrated CO(2-1) emission in 30 Doradus. The emission is concentrated in three large molecular complexes which had been mapped by Johansson et al. 1998 in CO(1-0). Namely the SW cloud (30Dor-10) the NE cloud (30Dor-6) and the N cloud (30Dor-13). The higher resolution data shows a more complex structure which can be separated into different smaller sizes clouds. Figure 1(b) shows the CO(2-1)/(1-0) ratio over all the region after convolving the CO(2-1) map to the CO(1-0) resolution. This ratio ranges between 0.5 and 1.1.

The higher sensitivity of the CO(2-1) observations revealed a series of small molecular clouds - clumps - located in between the SW and NE molecular clouds, not detected in the CO(1-0) observations. These are several dense regions that show a complicated velocity structure. We have been able to disentangle at least 8 CO clumps with sizes ranging from 3.0 to 7.0 pc, CO luminosities of 0.5×10^4 to 4.3×10^2 K km $s^{-1}$and virial masses 0.5×10^4 to 4.6×10^4 $M_{\odot}$.

2. N159: The study of the CO(2-1) emission line in this region has been done by Bolatto at al. (2000). An interesting result found by these authors is the unusually high CO(2-1)/(1-0) $\sim$ 3 in the molecular envelope of N159. Such high ratios are rarely detected in our Galaxy.

3. CO Arc: An interesting new feature of the LMC NANTEN CO survey is the CO arc located in the southeast part of the LMC (Fukui et al. 1999). Simultaneous observations in CO(2-1) and CO(1-0) at 40" spacing have been performed by the Nanten group in collaboration with the Swedish group at SEST (Mizuno, Johansson, private communication). First results of these observations indicate ratios from 0.7 to 0.9 for GMCs with no star formations and 0.8 to 1.3 for those associated with star formation.

4. SMC: In the SMC, the CO(2-1)/(1-0) ratios observed by our Large Programme data tend to be systematically higher than 1 and in some cases, eg N66C the ratio is found to be 2.4. Similarly, the N83/N84 region shows a CO(2-1)/CO(1-0) integrated line brightness ratio uniformly throughout most of the complex of 1.1. with two distinct regions showing unusually high ratios, larger than 2 (Bolatto et al. 2003).

3.3. The Isotopic Ratio

Israel et al. (2003) report the collection of all ^{13}CO(1-0) measurements done towards the peak positions of molecular clouds in the LMC and SMC mapped by the ESO-SEST Key Programme. The SMC data show relative low CO intensities I(CO)$<$ 10 K km s^{-1} and isotopic values ranging from 5 to 25. In the LMC, the molecular clouds show a larger spread of values. For molecular clouds with CO intensities I(CO)$>$ 30 K km s^{-1}, isotopic values show a similar value of $\sim$ 10. These clouds are associated with intense star forming regions. This value is about 2 times higher than the isotopic ratios of Galactic molecular cloud centers. Previous isotopic studies have been done mainly towards the strongest CO cloud in the LMC, N159, by Johansson at al. (1994), Heikkila et al. (1998) and Chin et al. (1997). Also, the brightest CO cloud in the SMC, LIRS36, was observed by Chin et al. (1998). These studies found ^{13}CO/^{12}CO ratios typically of 8 to 10 in the studied clouds which are associated with strong HII regions.

3.4. Other Molecules

Heikkila et al. (1998, 1999) reported the detection of $C^{18}O$, CS, SO, HCO^+, HNC, HNC, C_2H and H_2CO. In addition to these they reported detection of CH_3OH, CH_3CCH, tentative H_2CS and the first extra-galactic ortho-H_2S, in N159W in the LMC. They estimated kinetic temperatures of 25K in N159W and 15K in N27(LIRS49), respectively, and a number density of hydrogen of $(1-10)\times10^5$ cm^{-3} for N159W, and $(5-50)\times10^4$ cm^{-3} in N27. They concluded that the metallicity difference between the LMC and SMC does not seem to affect the physical state of the gas.

The molecular abundances determined by these authors are typically 5 to 20 time lower in N159W than in Galactic clouds. In the cloud 30Dor-10 (Johansson et al. 1998) near the center of 30 Dor region, the molecular abundance is on average 8 time lower than in the N159W cloud. This under-abundance is explained as due to the higher photo-dissociation rate in a region of higher FUV radiation field. The metallicity of the HII regions in the LMC and Galaxy differs by a factor of ~ 3, so in order to explain the difference in molecular abundances, a combination of lower metallicity and higher photo-dissociation rates is needed. Chin et al. (1996, 1997, 1998) found that, in four regions studied in the LMC (N159W, N44BC, N113, and N214D), HCO^+ is stronger than HCN, and HCN is stronger than HNC. The high relative HCO^+ intensities are consistent with high ionization from supernova remnants or young stars.

In the SMC cloud, N27 (LIRS 49), the molecular abundances derived are 6 times lower than in N159W. This result is attributed to a lower metallicity in the SMC. An alternative explanation to these under-abundances with respect to those found in N159W is a higher H/H_2 ratio in these clouds as compared to the rest of the sample observed.

Heikkila, Johansson, and Olofsson (1998), made a study of the $C^{18}O/C^{17}O$ ratio in four clouds in the LMC. and estimated an average gas-phase $C^{18}O/C^{17}O$ abundance ratio of 1.6 ± 0.3. This value is significantly lower, by factor of 5, than typical values found in Galactic clouds. In the SMC, $C^{18}O$ was not detected towards N27.

4. Discussion and Conclusions

The molecular gas in the Magellanic Clouds have been extensively studied and molecular cloud properties have been derived. In general, the CO luminosity of the clouds is lower than those galactic molecular clouds. The higher gas to dust ratio, and the lower metallicity are responsible for a lower amount of CO molecules as well as a larger photo-dissociation rate due to less dust shielding. Thus the CO molecules survive only in the dense regions. H_2 molecular gas can be much more extended and thus not completely traced by the CO emission. Very little diffuse extended CO is seen, diffuse CO between or surrounding CO discrete clouds is either very weak or absent.

Throughout the Magellanic Clouds, the emission CO line ratio ^{12}CO(2-1)/^{12}CO(1-0), is found to be close to unity. Optically thick CO emission arising from thermalized gas at $T > 10$ K yields brightness temperatures ratios R = CO(2-1)/(1-0) ~ 1. Deviations from these conditions, such as low temperatures or sub-thermal excitation in the gas with volume densities below the critical

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density of the CO(2-1) transition, $n_{crit} \sim 10^4$ cm^{-3} generally produce ratios less than 1. However, somewhat higher ratios are found, $\sim$ 1.2, both in the LMC and SMC. These are probably caused by a mixture of high and low optical depths in the molecular clouds and cloud envelopes. Hence, departures from the assumption of a homogeneous source characterized by a single temperature and a single column density occur.

Unusually high transition ratios are observed in N159 in the LMC, and in N83, SMC-N66C and other clouds in the SMC. Bolatto et al. (2000) discussed four possible origins for them: (1) self-absorbed ^{12}CO(1-0) emission, (2) optically thin emission from isothermal gas, (3) an ensemble of small optically thick isothermal clumps, and (4) optically thick emission with temperature gradients. For N159, they suggested that the high measured ratios were a direct consequence of the low metallicity of the medium. The results obtained in the SMC, in two regions in the N83/N84 complex, of R > 2, imply that the effect of metallicity is not straightforward. Bolatto et al. argue that the N83/N84 results are best explained by CO emission arising from an ensemble of small (R $\sim$ 0.1pc), warm ($T_{gas} \sim$ 40 K) clumps. This explanation is similar to that proposed by Lequeux et al. (1994) for the high ratios measured toward N66 and N88. We suggest this to be the most probable explanation for the high ratios (Rubio 2003; Mizuno, private communication) found in other SMC clouds. No evidence is found that self-absorbed CO(1-0) could be a possible explanation while higher resolution observations would greatly improve understanding of these results.

The majority of all LMC lines of sight detected in ^{13}CO have an isotopic emission ratio I(^{12}CO)/I(^{13}CO) of about 10, twice higher than found in Galactic star forming complexes. This ratio shows variations towards weak CO sources. The high ratios are found toward CO photo-dissociation regions at cloud edges while lower ratios are detected towards dense and cold molecular gas. This isotopic ratio probably reflects the lower CO abundance in the Magellanic Clouds and the strong radiation ambient conditions in these low metallicity galaxies.

4.1. The Conversion Factor

An important study of the molecular gas in the Magellanic Clouds is the determination of the relation between CO luminosity and molecular hydrogen column density. Observations with higher angular resolution have resolved the CO clouds and their virial masses were derived. At the resolution provided by SEST, we find in general that in the LMC, the conversion factor X is a factor 2 to 3 times larger than the Galactic factor. A similar result is found in the SMC. Virialization of the molecular clouds have been assumed in this determination. However, the physical properties derived from the CO(2-1) emission, the isotopic, and multi-line observations show that the CO clouds are very clumpy and that probably in the dense cores the conversion factor might tend to values similar to that derived in our Galaxy. An important result from these new studies is that the total CO luminosity in a determined volume remains the same independent of the different resolutions used in the observations. We have confirmed that the Nanten measured CO luminosity is the sum of the SEST CO luminosity of the clouds in different samples of regions in both LMC and SMC that have been mapped by both surveys. The same is true for the comparison between the Columbia survey and Nanten, and SEST. Thus, the CO emission only traces the total H_2 mass for regions where conditions are similar to those found in our Galaxy, most likely the densest part of the Magellanic Clouds CO clouds. The fact that the ISM does have less C and O, and therefore produces less CO, and that the gas-to-dust ratio is larger, providing less shielding and larger photo dissociation, is affecting the the size of the CO emitting region. Therefore, extragalactic CO observations, which have a low linear resolution due to the large distances, should consider this effect in systems that show important differences in their interstellar media. Also, systems with low metal content such as the galaxies formed in the early universe should show this effect. ALMA, with is sensitivity and extraordinary resolution, will be essential to perform a complete, detailed and deep study of the properties of molecular gas in low metallicity and low dust environments.

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References

Bolatto, A.D., et al. 2000, ApJ, 548, 234
Bolatto, A.D., et al. 2003, ApJ, 595, 167
Chin,Y.-N., et al. 1996, A&A, 305, 960
Chin,Y.-N., et al. 1997, A&A, 317, 548
Chin, Y.-N., et al. 1998, A&A, 330, 901
Fukui, Y., et al. 1999, PASJ,51, 745
Heikkila, A., Johansson, L.E.B.,& Olofsson, H. 1998, A&A. 332, 493
Heikkila, A., Johansson, L.E.B.,& Olofsson, H. 1999, A&A, 344, 817
Israel, F.P., et al. 1993, A&A, 270, 25 (Paper I)
Israel, F.P., et al. 2003, A&A, 406, 817 (Paper X)
Johansson, L.E.B., et al. 1994, A&A, 291, 89
Johansson, L.E.B., et al. 1998, A&A, 333, 657 (Paper VII)
Kurtz, C.M, & Dufour, R.J. 1998, Rev.Mex. Astron. Astrofis., 7, 202
Lequeux, J., et al. 1994, A&A, 292, 371
Mizuno et al. 2001, PASJ, 53, 971.
Rubio, M., et al. 1993a, A&A, 271, 1. (Paper II)
Rubio, M. Lequeux, J., & Boulanger, F. 1993b, A&A, 271, 9.(paper III)
Rubio, M. 1996, Proc. IAU Symp. 170, 265
Rubio M. 2003, In ESO Workshop: The ESO Large Programmes, Garching.