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Tracing the cold molecular gas reservoir through dust emission in the SMC

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Abstract. The amount of molecular gas is a key for understanding the future star formation in a galaxy. However, this quantity is difficult to infer as the cold H_2 is almost impossible to observe and, especially at low metallicities, CO only traces part of the clouds, keeping large envelopes of H_2 hidden from observations. In this context, millimeter dust emission tracing the cold and dense regions can be used as a tracer to unveil the total molecular gas masses. I present studies of a sample of giant molecular clouds in the Small Magellanic Cloud. These clouds have been observed in the millimeter and sub-millimeter continuum of dust emission: with SIMBA/*SEST* at 1.2 mm and the new LABOCA bolometer on *APEX* at 870 μm. Combining these with radio data for each cloud, the spectral energy distribution of dust emission are obtained and gas masses are inferred. The molecular cloud masses are found to be systematically larger than the virial masses deduced from CO emission. Therefore, the molecular gas mass in the SMC has been underestimated by CO observations, even through the dynamical masses. This result confirms what was previously observed by Bot *et al.* (2007). We discuss possible interpretations of the mass discrepancy observed: in the giant molecular clouds of the SMC, part of cloud's support against gravity could be given by a magnetic field. Alternatively, the inclusion of surface terms in the virial theorem for turbulent clouds could reproduce the observed results and the giant molecular clouds could be transient structures.

Keywords. dust, extinction, ISM: clouds, ISM: molecules, galaxies: individual (SMC), galaxies: ISM, Magellanic Clouds, sub-millimeter

1. Introduction

Star formation is fueled by the cold interstellar medium from the molecular clouds where this process takes place. The star formation rate in a galaxy therefore depends on the amount of molecular gas available. Most of the molecular gas in a galaxy lies in giant molecular clouds, but the quantity of H_2 remains difficult to estimate precisely since it is almost impossible to observe directly in cold interstellar regions. In this context, one has to rely on tracers and the CO molecule is the most widely used one from our solar neighborhood to distant galaxies.

In particular, the CO luminosity can be converted to a mass of molecular hydrogen through the $X_{\rm CO}$ factor defined as $N(\rm H_2)/I_{\rm CO}$. This factor has been well calibrated in our galaxy with different methods and a consensus is reached for $X_{\rm CO} \sim 2 \times 10^{20}$ mol cm^{-2} K km s^{-1}. However, variations of this factor with the environment is expected and is still debated. In particular, at low metallicities, the relationship between H_2 and CO remains unclear. Alternatively, one can use the CO data to observed line widths and therefore probe the dynamics of the clouds. Simplified forms of the virial theorem ($M = 190\, R\, \Delta\, V^2$, MacLaren *et al.* 1988) are largely used to determine molecular cloud masses. This method is applied to various scales ranging from cores, to giant molecular clouds, to galaxies as a whole. However, this assumes that clouds are virialized (bound) and the effects of external pressure or magnetic fields are ignored.

The Small Magellanic Cloud (SMC) is one of the closest and easiest to observe, low metallicity galaxy. Due to its proximity, molecular clouds in this galaxy can be resolved at various wavelengths by the observations. Numerous molecular clouds in the Magellanic Clouds were observed in CO lines (Rubio *et al.* 1993a,b, 1996; Mizuno *et al.* 2001) and were found to have weak CO emission. If the CO molecule is tracing accurately the molecular gas, then the star formation per unit molecular gas in the SMC is higher than in most galaxies. Such an effect is observed in other low metallicity dwarf galaxies (Leroy *et al.* 2006a) and could be an evolutionary effect or the fact that CO observations largely underestimate the amount of molecular gas in these conditions. Indeed, at low metallicities, CO can be photodissociated and trace only the densest parts of the clouds, while H_2 molecules have the capacity to self-shield and would be present at larger radius than the CO molecule.

To better understand the total molecular content and its relationship to CO emission, other tracers of the molecular gas at low metallicities have been looked for. Dust continuum emission can be used to trace the dense and cold interstellar medium where the gas is molecular and it can therefore be used to unveil the total mass of molecular gas in clouds. Leroy *et al.* (2006b) attempted to do so using far infrared emission observed with Spitzer data in the SMC. In dense regions, they observed large quantities of dust not associated to either H I or CO emission. However, the dust emission in the far-infrared is sensitive to the dust temperature, leading to large uncertainties in the cloud's masses. In the sub-millimeter and the millimeter range, dust emission is difficult to observe but depends only linearly on the dust temperature and is optically thin. Rubio *et al.* (2004) observed for the first time with SIMBA on the *SEST* telescope, the 1.2 mm emission from dust in a quiescent molecular cloud in the SMC. The mass of molecular gas deduced was several times higher than the mass deduced from CO observations in this cloud. Bot *et al.* (2007) extended this study with SIMBA data to a larger sample of molecular clouds in the south-west region of the SMC. In all clouds, the gas mass deduced from the dust emission is systematically larger than the virial mass deduced from CO, even for conservative values of the dust emissivities and free-free contribution to the millimeter emission. All these studies come to agreement in the fact that molecular clouds in the SMC are more massive than what can be deduced from CO emission or dynamical masses. This mass difference is understood in a scenario where CO traces only the densest parts of the molecular clouds and the clouds are partially supported by a magnetic field (i.e. the motions in the cloud do not trace the gravitational potential). However, these results need to be confirmed with observations in the sub-millimeter range in order to more certainly exclude the contamination of the fluxes by free-free emission, as well as unknown instrumental effects, etc.

2. 870 μm emission in the south west region of the SMC

We present new observations of the sample of molecular clouds in the south west region of the SMC taken with the LABOCA camera on the *APEX* telescope (Fig. 1). These observations at 870 μm complement the SIMBA data at 1.2 mm. Sub-millimeter emission is detected in the whole region and all the giant molecular clouds that were observed in CO(1–0) are detected.

For every cloud detected in CO, we compute the integrated emission at 870 μm as observed with LABOCA and compare it to the emission at 1.2 mm as observed by SIMBA and radio emission at 4.8 and 8.64 GHz from *ATCA* (Dickel *et al.*, this volume). Fig. 2 presents the spectral energy distribution obtained that way for each giant molecular cloud. By extrapolating the radio emission, we observe that the sub-millimeter and millimeter emission are dominated by dust emission and the contribution of free-free emission to the (sub-)millimeter fluxes is negligible. Furthermore, the 870 μm and 1.2 mm fluxes are consistent with a standard dust emission law, i.e. a modified blackbody with a spectral index of 2 ($I_\nu \propto \nu^2 B_\nu T_{\rm dust}$). The LABOCA fluxes in south west region of the Small Magellanic Cloud can therefore safely be used to deduce molecular gas masses given the dust emissivity at 870 μm is known.

3. Molecular cloud masses

We computed a reference emissivity at 870 μm for dust associated to molecular gas. This was done using FIRAS data at 850 μm and correlating it with LAB H I (Kalberla *et al.* 2005) and CO data (Dame *et al.* 2001) in the molecular ring of the Milky Way. The method used is similar to the one described in Bot *et al.* (2007) and we obtain: $\epsilon_{870}(\mathrm{H_2}) = (2.32 \pm 0.03) \times 10^{-26}$ at^{-1} cm^2. Taking this value and assuming a dust to gas ratio 0.17 times solar, we deduce molecular gas masses from the LABOCA 870 μm emission for each giant molecular cloud (as defined by CO) in the south west region of the SMC.

The masses obtained from the dust sub-millimeter emission are compared to virial masses deduced from the CO line-widths for the same clouds. The comparison is shown in Fig. 3: for all the clouds detected in CO in this region of the SMC, the masses deduced

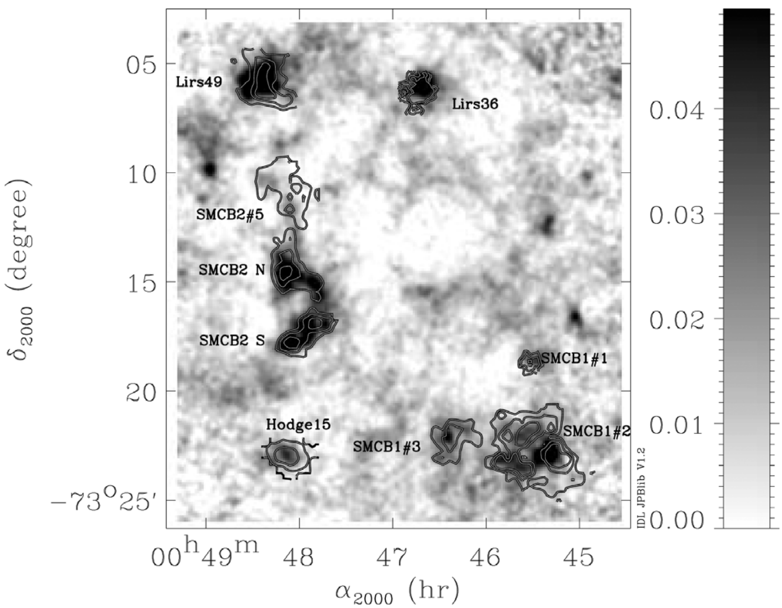

Figure 1. LABOCA image in the south west region of the SMC with CO contours overlaid. All the molecular clouds observed in CO are detected at 870 μm.

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from the 870 μm dust emission are systematically larger than the one deduced from the virial theorem (black rhombs). These results are completely consistent with what is obtained from SIMBA data (green triangles). For comparison, the same method was applied to a sample of similar clouds in the Galaxy (Bot *et al.* 2007, noted BBR07) using FIRAS data at 850 μm. For the galactic clouds, the trend observed is the complete opposite: the virial masses are always larger than the mass deduced from the dust sub-millimeter emission. These results confirm what was observed previously by Bot *et al.* (2007). In the low metallicity environment of the SMC, the molecular gas mass of giant molecular clouds is much larger than what is inferred from CO data, even when computed from the dynamical masses.

Furthermore, there seems to be a trend between the mass ratio ($M_{\rm vir}/M_{\rm mm}$) with respect to the mass deduced from the millimeter (believed to be the true mass of the clouds): the larger the mass of a giant molecular cloud, the smaller the mass ratio ($M_{\rm vir}/M_{\rm mm}$).

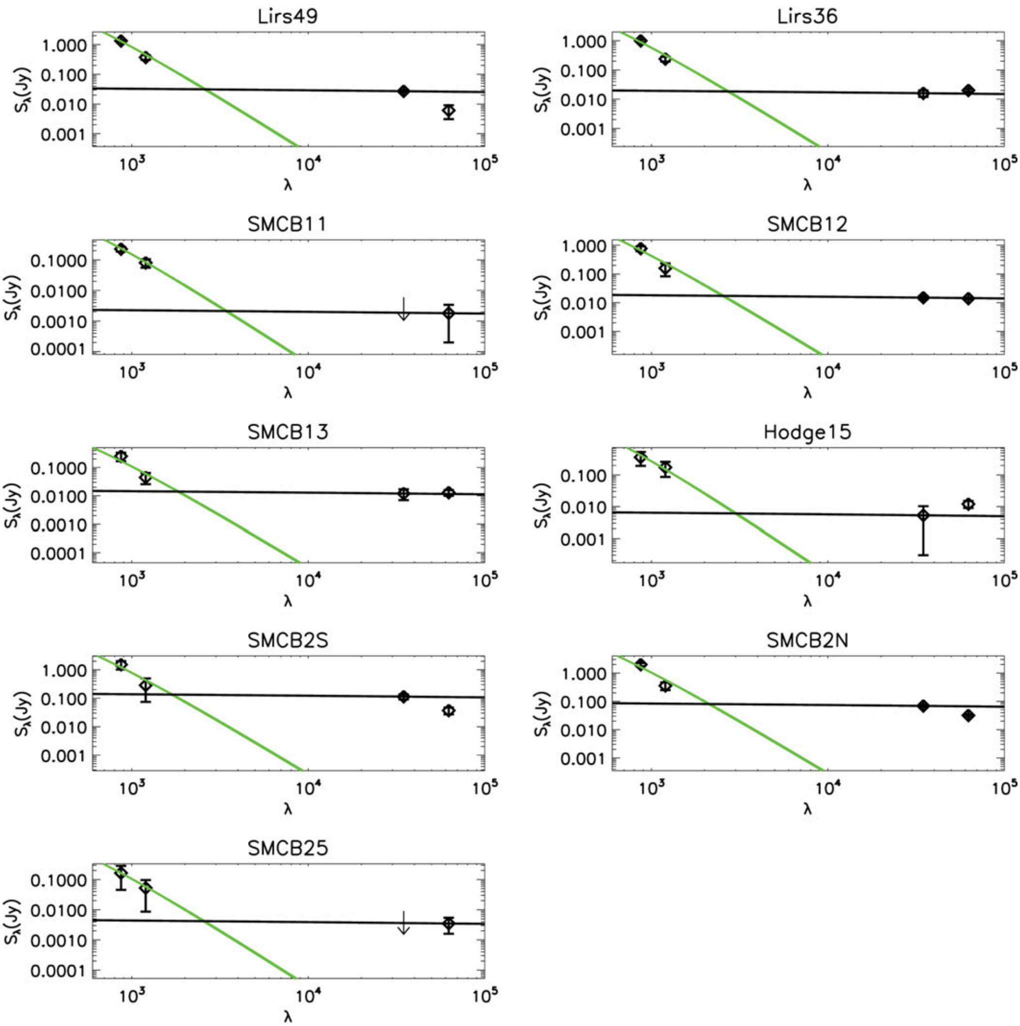

Figure 2. Spectral energy distribution from the far-infrared to the radio observed for each cloud. The fluxes observed at 870 μm and 1.2 mm are consistent with dust emission with an emissivity index of 2. Radio fluxes for the same regions clearly show that the sub-millimeter and millimeter emission detected is dominated by dust emission rather than free-free.

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4. Discussion

The overestimation of the mass of the clouds by the virial theorem for the Galactic cloud, was observed previously (Solomon *et al.* 1987) and is interpreted as the effect of external pressure on the molecular clouds. On the other hand, the underestimation of the mass of the clouds by the virial theorem in the giant molecular clouds of the SMC was unexpected and is more difficult to explain. Bot *et al.* (2007) used the general version of the virial theorem and showed that additional support to the cloud by a magnetic field could explain this effect. Such a magnetic support has been observed in our galaxy, but on much smaller scales (e.g., Wong *et al.* 2008). This magnetic field support could be more salient in the SMC due to the fact that the giant molecular clouds are denser than their galactic counterparts. However, the continuity between the galactic pressure confined molecular clouds and the SMC magnetically supported clouds is difficult to understand in that scheme.

Alternatively, the clouds in the SMC could be transient turbulent structures. Recently, Dib *et al.* (2007) presented a comprehensive model of three dimensional, isothermal, turbulent and magnetized molecular clouds and assess their virialization and the importance of the different terms in the virial equation. One point raised is the importance of the inclusion of surface terms in the virial theorem: surface thermal energy, surface kinetic energy and surface magnetic energy. Applying classical indicators on a simulation of supercritical turbulent clouds, mostly transient in nature, they observe a relationship between $M_{\rm vir}/M$ and M completely consistent with the one we observe. The mass discrepancy as well as the trend we observe could then be reproduced for short lived, turbulent clouds and would reflect their dynamical evolution.

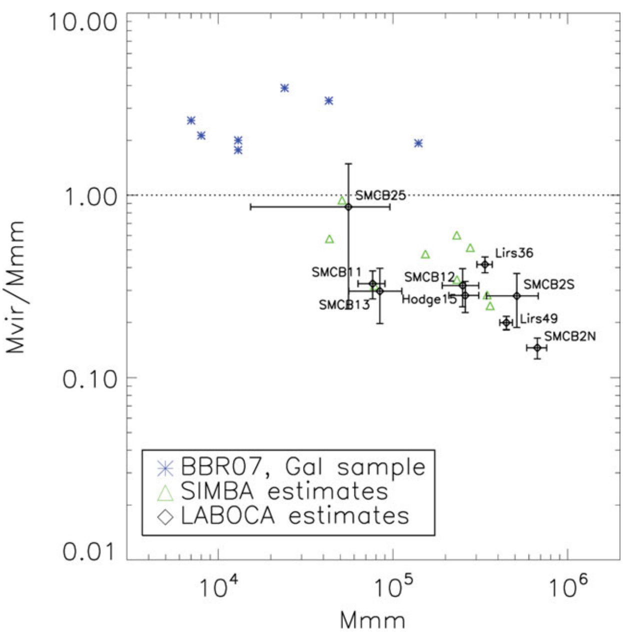

Figure 3. Comparison between the two molecular mass estimates: dust emission and virial masses. Galactic giant molecular clouds studied with the same method are shown for comparison (Bot *et al.* 2007). In the SMC, the molecular mass deduced from the 870 μm emission (black rhombs) or 1.2 mm emission (green triangles) are systematically larger than virial masses.

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5. Conclusion

We presented new LABOCA data in the south west region of the Small Magellanic Cloud. All the giant molecular clouds that were observed in CO are detected. By comparing to SIMBA and radio data, we show that the sub-millimeter and millimeter emission of these clouds are dominated by normal dust emission.

For each giant molecular cloud observed both with LABOCA and CO (1–0), we compute a molecular gas mass from the sub-millimeter emission and compare it to the virial mass deduced from the CO line widths in the same regions. We confirm the results observed by Bot *et al.* (2007): in the SMC, the virial mass systematically underestimate the true mass of the molecular clouds. Applying the same method to a sample of similar clouds in our galaxy shows the reverse (the virial masses under-estimate the true mass of the clouds). We also observe a possible trend from the Galactic clouds to the SMC one: the mass ratio $M_{\rm vir}/M$ seems to decrease with the true molecular mass of the clouds.

The mass discrepancy between the two methods (from the dust emission or the virial theorem) can be understood as follows: in the galaxy, the clouds are pressure confined, while in the SMC, the clouds could be partially supported by magnetic fields. The difference between these two regimes could be due to the different densities between the two clouds samples. However, an alternative model where clouds are transient and the surface terms in the virial theorem are important could also reproduce the mass discrepancy and the trend observed.

This study shows clearly how sub-millimeter and millimeter observations of molecular clouds can shed new light on the molecular content and the state of the molecular clouds. Similar studies on wider samples of clouds and in various environments will have to be pursued to bring new insights on the molecular content of galaxies and the relationship with star formation.

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