Session 2:

Molecular Clouds:
Distribution, Large-scale Properties, Formation, Evolution

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The Molecular Cloud Population of the Large Magellanic Cloud

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Abstract. We have mapped an extensive sample of molecular clouds in the Large Magellanic Cloud (LMC) at 11 pc resolution in the CO(1-0) line as part of the Magellanic Mopra Assessment (MAGMA). We identify clouds as regions of connected CO emission and determine their sizes, line widths, and fluxes. We find that GMCs are not preferentially located in regions of high H I line width or velocity gradient, and that there is no clear H I column density threshold for CO detection. The luminosity function of CO clouds is steeper than $dN/dL \propto L^{-2}$, suggesting a substantial fraction of mass in low-mass clouds. The correlation between size and linewidth, while apparent for the largest emission structures, breaks down when those structures are decomposed into smaller structures. The virial parameter (the ratio of a cloud's kinetic to gravitational energy) shows a wide range of values and exhibits no clear trends with the likelihood of hosting young stellar object (YSO) candidates, suggesting that this parameter is a poor reflection of the evolutionary state of a cloud. More massive GMCs are more likely to harbor a YSO candidate, and more luminous YSOs are more likely to be coincident with detectable CO emission, confirming GMCs as the principal sites of massive star formation.

Keywords. ISM: molecules — Magellanic Clouds — radio lines: ISM — stars: formation

1. Introduction

The Large Magellanic Cloud (LMC) is the nearest actively star-forming galaxy to our own ($d \approx 50$ kpc), yet the distribution of its CO emission has been revealed in detail only recently. The first complete CO map, at a (smoothed) resolution of 12′, was published by Cohen *et al.* (1988), based on observations with the 1.2-m Columbia Millimeter-Wave Telescope. Subsequent CO mapping was undertaken by the 4-m NANTEN telescope, at a resolution of ∼3′ (Fukui *et al.* 1999, 2008). The Magellanic Mopra Assessment (MAGMA), a large program at the Australia Telescope National Facility's Mopra 22-m telescope, forms a natural extension of the NANTEN surveys: the targeted mapping of known CO complexes in the Magellanic Clouds at improved angular resolution (45″, or 11 pc at a distance of 50 kpc), adequate to resolve the largest giant molecular clouds (GMCs). In the LMC, MAGMA has targeted 114 GMCs with CO luminosity >7000 K km s^{-1} pc^2 and peak CO intensity >1 K km s^{-1}. These constitute roughly 45% of the catalogued NANTEN GMCs by number, but 80% of the total CO flux. More information about MAGMA, including access to data products, is available online at http://mmwave.astro.illinois.edu/magma.

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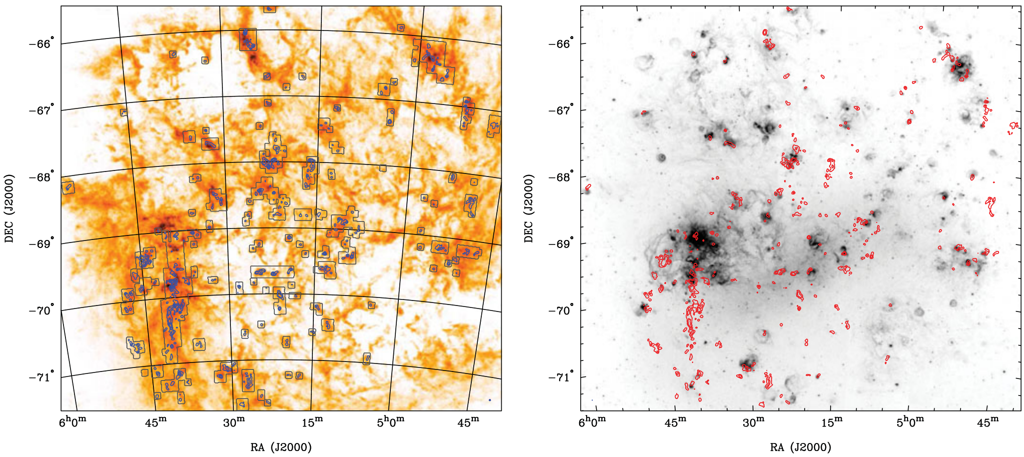

Figure 1. CO intensity contours from MAGMA, overlaid on a peak H I brightness temperature image from Kim *et al.* (2003) (*left*) and an Hα+continuum image from MCELS (Smith *et al.* 1999) (*right*). Regions observed in CO are outlined by gray boxes.

2. Overview and Initial Science Results

Figure 1 provides on overview of the MAGMA data, with CO intensity contours overlaid on a peak H I brightness temperature image (*left*) and an Hα+continuum image (*right*). Rectangular contours on the left panel indicate the regions mapped with Mopra. Since peak H I brightness is a good tracer of cold H I, it is not surprising that it is well associated with CO emission. On the other hand, the correlation of CO emission with ionized gas, as traced by Hα emission, is more complex. Many molecular clouds show little ionized gas, and vice versa. This suggests that molecular clouds are quite rapidly destroyed once massive stars form within them.

The improved resolution of MAGMA reveals many substructures within the larger GMCs. We use the CPROPS algorithm by Rosolowsky & Leroy (2006) to automatically identify and catalogue significant emission regions. An initial CPROPS analysis identifies the largest contiguous emission regions, dubbed "islands." For each island we measure the major and minor axes, velocity dispersion, and flux. Subsequent CPROPS runs can be tuned to identify structures similar in size to Galactic GMCs, or to decompose structure down to the $\sim$10 pc resolution of the CO maps. Since these different analyses reveal different aspects of cloud structure, we have generated three nested catalogs of CO clouds, which are presented in Wong *et al.* (2011).

2.1. *Under What Conditions to Atomic Clouds Become Molecular?*

From an analysis of H_2 photodissociation equilibrium, McKee & Krumholz (2010) predict that the molecular gas fraction rises rapidly with H I column density at a characteristic column density determined by the metallicity. Assuming a roughly uniform metallicity for the LMC, we would expect CO emission to occur only above a minimum H I surface density. However, a pixel-by-pixel comparison of NANTEN CO and ATCA H I maps (Wong *et al.* 2009) found CO emission over a wide range of H I intensity. Most notably, even at the highest H I column densities, the probability of CO detection is only about 1/3. The molecular fraction is therefore not a simple function of H I intensity: significant H I column density appears necessary but not sufficient for the formation of CO clouds. Perhaps the formation of CO introduces additional dependencies, or perhaps not all of the gas which contributes to 21-cm emission takes part in shielding the molecular gas.

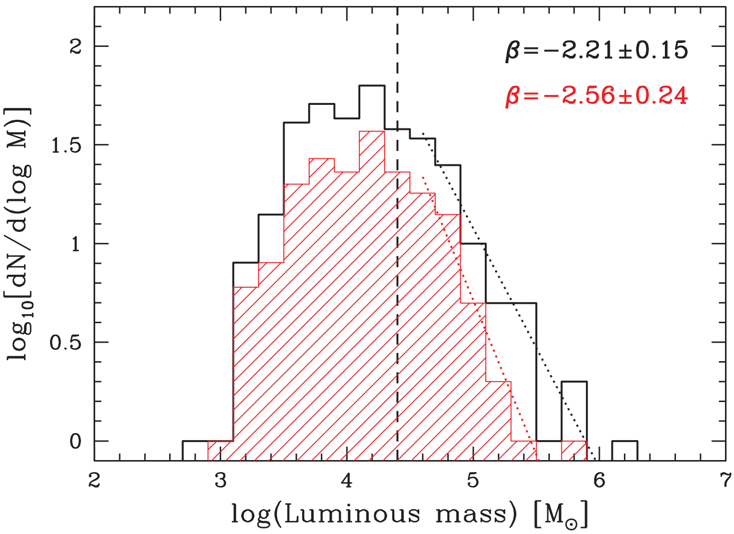

Figure 2. Mass spectrum of CO "islands"; the red, shaded histogram is for the isolated sub-sample.

It has also been suggested that molecular clouds form as a result of colliding neutral gas flows. In that case, H I velocity dispersion might be expected to correlate with CO emission. This is not the case, as also shown by Wong *et al.* (2009): the likelihood of detecting CO emission is the same for all H I line widths. Indeed, we find many GMCs which appear to be associated with narrow H I line widths. Local velocity gradients in the H I are another possible indicator of gas flows. Yet, a preliminary analysis of line-of-sight velocity gradients suggests that large gradients are found in regions *lacking* CO emission. This is consistent with scenarios in which CO emission becomes prominent well after the cloud is assembled.

2.2. *Are Giant Molecular Cloud Properties Universal?*

Solomon *et al.* (1987) characterized several basic relationships for molecular clouds, commonly known as Larson's Laws. These include correlations between size and linewidth and between CO luminosity and virial mass. We see these correlations in the MAGMA clouds as well, although with some differences in normalization. What is notable, however, is the large scatter in these relationships, much larger than the measurement uncertainties. It is common to interpret Larson's Laws as evidence for virial equilibrium, but if so, the variation in linewidth at a given size corresponds to a factor of 20 variation in mass surface density, and the variation in CO luminosity at a given virial mass corresponds to a factor of 10 variation in the CO-to-H_2 conversion factor (Hughes *et al.* 2010).

Not only is the scatter large, but it is also scale dependent. Further decomposition breaks larger clouds into smaller clouds with a wide range of line widths at given size. Does this simply reflect the stochastic nature of turbulence, so that underlying relationships are only apparent in ensemble averages? Or are we seeing the importance of small-scale stirring by sources internal to the GMCs, leading to sharp differences in characteristics for clumps of similar size? These questions still need further investigation.

2.3. *Is Most of the H_2 Mass in High or Low Mass Clouds?*

One of the basic properties of a population of molecular clouds is its mass spectrum, which can be derived from the luminosity function if mass is assumed proportional to

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L_{CO}. It is common to fit a power law to the bright end of the luminosity function under the assumption that the faint end is incompletely sampled. For a slope $\beta > -2$ most of the mass is in high-mass clouds; that appears to be the situation in the inner Galaxy, according to Solomon *et al.* (1987). In the LMC, however, the slope appears to be < -2 (Figure 2). The slope is even steeper for the subset of clouds that are isolated and thus less susceptible to blending (red histogram). If galaxies like the LMC put most of their molecular gas in low-mass clouds, this could have a significant effect on estimating H_2 masses and star formation efficiencies from CO mapping, because of sensitivity limits.

2.4. *What is the Relationship Between GMCs and Star Formation?*

Finally we have investigated the relationship between GMCs and star formation, the latter traced by the *Spitzer* source catalogs of Gruendl & Chu (2009) and Whitney *et al.* (2008). We confirm that GMCs are indeed the principal sites of massive star formation. If we compare the locations of GMCs with those of young stellar objects identified from *Spitzer* photometry, the most luminous YSOs are overwhelmingly found where there is detectable CO emission. Thus, the improved spatial resolution of MAGMA has not resolved offsets where YSOs are no longer associated with molecular gas due to evolution. The *Spitzer*-selected sources must represent a very early stage in stellar evolution.

On the other hand, not all GMCs are currently forming stars. While more massive GMCs are more likely to host YSOs, only about half of the molecular clouds in total harbor candidate protostars. The likelihood of harboring a massive YSO is a strongly increasing function of GMC mass up to 10^5 solar masses. We don't yet know whether the lower-mass clouds are truly not forming stars (being in some different stage of evolution) or whether they are only forming lower mass stars, but this is an area which is ripe for improvement, as the combination of the *Spitzer* and *Herschel* surveys will allow more complete SED modeling of embedded sources.

While GMC mass correlates strongly with star formation properties, the ratio of kinetic to gravitational energy, measured by the virial parameter ($\alpha_{\rm vir}$), does not. The virial parameter is often used to gauge the importance of self-gravity for a cloud. We find no correlation of $\alpha_{\rm vir}$ with the likelihood of a GMC harboring a YSO, suggesting that $\alpha_{\rm vir}$ is a poor reflection of the evolutionary state of a cloud.

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