From Interstellar Clouds to Star-Forming Galaxies: Universal Processes?
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Resolving the Transition from Molecular to Atomic at 1/5 Solar Metallicity in the Small Magellanic Cloud

Katherine E. Jameson[1], Alberto D. Bolatto[1], Mark Wolfire[1], Monica Rubio[2], Rodrigo Herrera Camus[1,3] and the HS^3 Collaboration

[1]Astronomy Department and Laboratory for Millimeter-wave Astronomy, University of Maryland, College Park, MD, 20742, USA
email: kjameson@astro.umd.edu

[2]Departamento de Astronomía, Universidad de Chile, Camino El Observatorio 1515, Casilla 36-D, Santiago, Chile

[3]Max-Planck-Institut für Extraterrestrische Physik, Giessenbachstrasse, D-85748 Garching, Germany

Abstract. At a distance of 61 kpc, the Small Magellanic Cloud (SMC) affords an absolutely unique view of the low metallicity star-forming interstellar medium, providing the nearest laboratory to study processes relevant to star formation at high redshifts. We present new ALMA 7m-array maps of ^{12}CO and ^{13}CO $(2-1)$ for one of the four observed regions in the Southwest Bar of the SMC. These maps are the first high-resolution ($\sim 6'' \sim 1.7$ pc) images of CO in a molecular cloud at 1/5 Solar metallicity. We show the structure of photodissociation regions for the first time at 1/5 Solar metallicity by combining the new ALMA data with Herschel maps of [C II] and [O I]. We present preliminary evidence that there is extended, faint ^{12}CO $(2-1)$ emission near where we expect the H I-to-H$_2$ transition. We also compare our data to the low metallicity 3D simulations by Glover & Mac Low (2011) and Shetty *et al.* (2011).

Keywords. ISM: clouds, ISM: structure, galaxies: ISM, Magellanic Clouds

1. Introduction

Due to its proximity and our ability to achieve high spatial resolution, the SMC provides the ideal laboratory to study detailed properties of the molecular gas in star-forming regions in a low mass, $M_{*,\rm SMC} = 3 \times 10^8\ M_\odot$ (Skibba *et al.* 2012), and low metallicity, $Z_{\rm SMC} \sim 1/5\ Z_\odot$ (Pagel 2003), environment. In low metallicity environments ^{12}CO, the most common tracer of the total amount of molecular gas (dominated by H$_2$), emits weakly and often goes undetected. The SMC has been studied extensively in ^{12}CO with the earliest surveys completed using the Columbia 1.2m (Rubio *et al.* 1991). The early survey of both Clouds (Israel *et al.* 1993) and of the Southwest Bar of the SMC (Rubio *et al.* 1993) using the Swedish-ESO Submillimetre Telescope (SEST) showed the CO emission to be under-luminous compared to the Milky Way by a factor of a few at small scales ($\sim$10 pc) and by $\sim 10-20$ at large scales ($\sim$200 pc) in the SMC. A "CO-faint" molecular phase is predicted by analytical and numerical models that show the CO abundance drops off below a mean visual extinction of $A_V \sim 2$ mag (Wolfire *et al.* 2010; Glover & Mac Low 2011; Shetty *et al.* 2011) where most carbon exists as C$^+$ while H$_2$ remains molecular because it is strongly self-shielding (Tielens & Hollenbach 1985; Wolfire *et al.* 1989; Kaufman *et al.* 1999). Studies of the SMC find this phase to encompass $80\%-90\%$ of all the H$_2$ (Israel 1997; Pak *et al.* 1998; Leroy *et al.* 2007; Leroy *et al.* 2011; Bolatto *et al.* 2011), likely dominating the molecular reservoir available to star formation.

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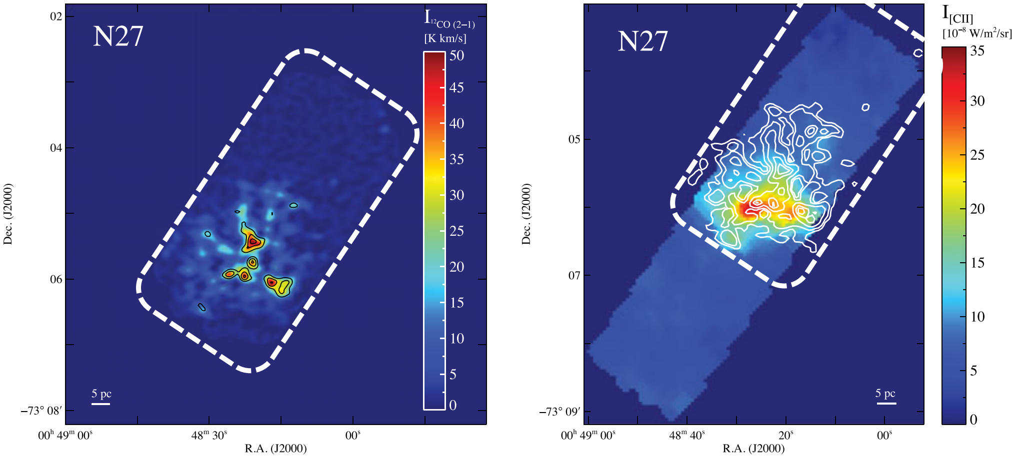

Figure 1. Left: Integrated intensity map of the combined ALMA 7m-array and APEX single-dish ^{12}CO $(2-1)$ image of the N27 region with black contours showing the ^{13}CO $(2-1)$ integrated intensity map at 2, 4, and 6 K km s^{-1} (beam size $\sim 7'' \times 5''$). In both panels the dashed white lines shows the approximate coverage of the ALMA 7-m array map. Right: Image of the [C II] integrated intensity for the N27 region with white contours showing the combined CO integrated intensity map at 3, 6, 15, 30, 40, and 50 K km s^{-1}. We see evidence of faint ^{12}CO emission out to low A_V and close to the expected atomic-to-molecular transition, and there is similarity between the [C II] and CO structure, which suggests that CO is tracing the molecular cloud structure.

The “CO-faint” molecular gas can be traced using diffuse γ-rays, dust continuum emission, and [C II] and [O I] line emission. Large-scale maps of the total molecular gas in the SMC have been made using dust continuum emission using *Spitzer* data (Leroy *et al.* 2007; Leroy *et al.* 2009; Bolatto *et al.* 2011), and more recently *Herschel* data (Jameson *et al.* 2015a), that show more extended molecular gas than what is traced by the large-scale NANTEN ^{12}CO map (Mizuno *et al.* 2001). Using the dust-based molecular gas estimate, Jameson *et al.* (2015a) finds no strong evidence that low metallicity affects the large-scale relationship between star formation and molecular gas, but metallicity is expected to affect the small-scale structure of the molecular gas and their surrounding photodissociation regions. The emission from [C II] can also trace the “CO-faint” molecular phase (e.g., Madden *et al.* 1997; Pineda *et al.* 2013), and observations from *Herschel* allow us to attain high resolution ($\sim 10''$) [C II] maps. When combined with new high resolution ^{12}CO maps from ALMA ($\sim 6''$ resolution), we can study the structure of the molecular gas and resolve the H I-to-H_2 transition. We present new *Herschel* [C II] and ALMA CO data for one of the targeted regions in the Southwest Bar of the SMC and show that there appears to be faint CO emission near the H I-to-H_2 transition.

2. Observations

Our results are based on our new ALMA 7m-array CO observations and *Herschel* [C II] and [O I] data. The *Herschel* data come from the *Herschel* Spectroscopic Survey of the SMC (HS^3; Jameson *et al.* 2015b). The survey consists of four $1.5' \times 6'$ strips covering star-forming regions and one $2' \times 2'$ map targeted at a peak in the dust-based molecular gas estimate not detected in the NANTEN ^{12}CO map. The regions sample a range of radiation field strength, star formation, and detected molecular gas in the Southwest Bar and in N83/N84 of the SMC. We mapped four approximately $1.5' \times 3'$

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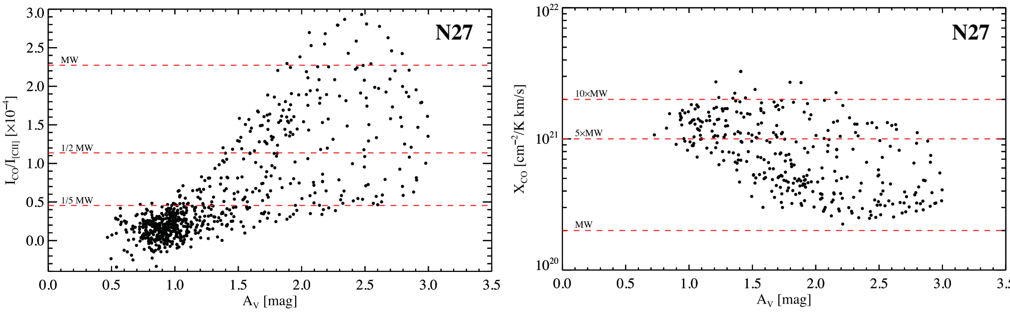

Figure 2. Left: The ratio of the integrated intensity of ^{12}CO (using the APEX ^{12}CO $(2-1)$ data and assuming thermalized emission to convert to $(1-0)$) to that of [C II] as a function of A_V for the N27 region in the SMC. The red dashed lines indicate different scalings of the canonical value for the Milky Way of $\sim 1/4400$ (Stacey *et al.* 1991). Right: The CO-to-H_2 conversion factor (X_{CO}) using [C II]-based estimate of N_{H_2} (assuming all [C II] emission comes from molecular gas) with $\geqslant 3\sigma$ ^{12}CO $(2-1)$ detections for the N27 region. The red dashed lines show different scalings of X_{CO} for the Milky Way of 2×10^{20} cm^{-2} (K km s^{-1})$^{-1}$ (Bolatto *et al.* 2013).

regions overlapping the HS^3 regions in ^{12}CO, ^{13}CO, and C^{18}O $(2-1)$ in the Southwest Bar with the ALMA 7m-array (resolution $\sim 6''$). The ALMA 7m-array maps have been combined with single-dish data from APEX ($\theta = 29.5''$; Rubio *et al.* 2015). For the preliminary results, we focus on the N27 region.

3. Preliminary Results

The [C II] and [O I] lines were detected ($S/N \gtrsim 3$) throughout all of the HS^3 regions. The ALMA 7m-array data shows clear detections of ^{12}CO and ^{13}CO $(2-1)$ emission in all of the regions, but C^{18}O is not detected (see Figure 1). In N27, we find ^{12}CO/^{13}CO ratios of $\sim 10-15$ in the peaks of the ^{12}CO map, which is consistent with previous measurements (Israel *et al.* 2003) and the typical ratios observed in the Milky Way. We see good correspondence between the ^{12}CO and [C II] emission and a fairly flat [O I]/[C II] ratio of ~ 0.3 across the regions. We investigate the structure of the photodissociation region and molecular cloud by using the visual extinction (A_V) as an indicator of depth within the cloud. The optical depth at 160 μm (τ_{160}) map from Lee *et al.* (2015) is converted to A_V using $A_V \sim 2200\tau_{160}$. The left panel of Figure 2 shows that the CO/[C II] ratio in N27 tends to increase at higher A_V deeper into the cloud and reach ratios similar to the value found in the Milky Way. Finding CO/[C II] and ^{12}CO/^{13}CO ratios similar to the Milky Way is consistent with theoretical expectations that once enough dust shielding is built up, the structure at low metallicity will resemble that of a high metallicity cloud.

An $A_V \sim 1$ corresponds to the typical extinction where ^{12}CO becomes optically thick. Our observation of faint ^{12}CO emission at $A_V < 1$ indicates that we are tracing optically thin ^{12}CO emission that corresponds to the "CO-faint" molecular gas (Wolfire *et al.* 2010). Figure 2 shows [C II] emission from the cloud depths we would expect to see a significant amount of "CO-faint" molecular gas and we have some detections of ^{12}CO $(2-1)$ down to an $A_V \sim 0.5$, which is close to the expected range for the H I-to-H_2 ($A_V \sim 0.2-0.4$). This suggests that this translucent molecular phase is "CO-faint" as opposed to the terminology that refers to it as "CO-dark" gas. The lower CO/[C II]ratios relative to the Milky Way value is likely indicating the presence of this this "CO-faint" component where the carbon primarily exists as C$^+$ and not as CO.

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The extended, low level [C II] emission can potentially emanate from ionized gas, warm neutral medium (WNM), cold neutral medium (CNM), a translucent molecular phase, or some combination. The HS^3 data includes [N II] observations, but there are no detections in the SMC regions, which indicates that the ionized gas is not contributing to the [C II] emission. The [O I]/[C II] ratio is a good indicator of the density of the gas, and comparing the ratio values to new heating and cooling curves for the SMC from Wolfire *et al.* (2015) show that the values we observe indicate densities of $n \sim 100 - 300$ cm^{-3}. These densities correspond to the CNM and potentially molecular gas. Combined with the observation that the extended [C II] and ^{12}CO emission structure is similar to that seen for the mid-IR H_2 rotational lines, it is likely that this gas contains a molecular component.

We then make the simplifying assumption that all of the [C II] emission originates from H_2 gas, and convert the observed [C II] intensity into an H_2 column density ($N_{\rm H_2}$) using the [C II] cooling curve for the SMC from Wolfire *et al.* (2015). This produces [C II]-based estimates of $N_{\rm H_2}$ $1 - 2 \times 10^{21}$ cm^{-2}. Using these values of $N_{\rm H_2}$, we estimate the ^{12}CO-to-H_2 conversion factor X_{CO} (see Figure 2, right panel). The general trend of decreasing X_{CO} with increasing A_V is consistent with the results for a LMC/SMC-type molecular cloud from Shetty *et al.* (2011) and can be explained by the enhanced photodissociation of CO in the outskirts of the cloud at lower metallicity.

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