Resolving the Transition from Molecular to Atomic at 1/5 Solar Metallicity in the Small Magellanic Cloud

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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 ¹²CO and ¹³CO (2 − 1) for one of the four observed regions in the Southwest Bar of the SMC. These maps are the first high-resolution (∼6” ∼ 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 [CⅡ] and [OⅠ]. We present preliminary evidence that there is extended, faint ¹²CO (2 − 1) emission near where we expect the HⅠ- to-H₂ 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, \(M_{SMC} = 3 \times 10^8 M_\odot\) (Skibba et al. 2012), and low metallicity, \(Z_{SMC} \sim 1/5 Z_\odot\) (Pagel 2003), environment. In low metallicity environments ¹²CO, the most common tracer of the total amount of molecular gas (dominated by H₂), emits weakly and often goes undetected. The SMC has been studied extensively in ¹²CO 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 (∼10 pc) and by ∼10 – 20 at large scales (∼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 H₂ 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 H₂ (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 $^{12}\text{CO} (2 - 1)$ image of the N27 region with black contours showing the $^{13}\text{CO} (2 - 1)$ 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 show the approximate coverage of the ALMA 7-m array map. Right: Image of the [C\textsc{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 $^{12}\text{CO}$ emission out to low $A_V$ and close to the expected atomic-to-molecular transition, and there is similarity between the [C\textsc{ii}] and CO structure, which suggests that CO is tracing the molecular cloud structure.

The “CO-faint” molecular gas can be traced using diffuse $\gamma$-rays, dust continuum emission, and [C\textsc{ii}] and [O\textsc{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 $^{12}\text{CO}$ 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\textsc{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\textsc{ii}] maps. When combined with new high resolution $^{12}\text{CO}$ maps from ALMA ($\sim 6''$ resolution), we can study the structure of the molecular gas and resolve the H\textsc{i}-to-H$_2$ transition. We present new Herschel [C\textsc{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\textsc{i}-to-H$_2$ transition.

2. Observations

Our results are based on our new ALMA 7m-array CO observations and Herschel [C\textsc{ii}] and [O\textsc{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 $^{12}\text{CO}$ 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 $1.5' \times 3'$
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 ∼ 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 ∼ 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 $\mu$m ($\tau_{160}$) 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 $A_V$ ∼ 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.
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 ($N_{H_2}$) using the [C ii] cooling curve for the SMC from Wolfire et al. (2015). This produces [C ii]-based estimates of $N_{H_2} = 1 - 2 \times 10^{21}$ cm$^{-2}$. Using these values of $N_{H_2}$, 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.

References

Jameson, K. E., Bolatto, A. D., Wolfire, M., et al. 2015, in prep
Rubio, M., Bolatto, A. D., Jameson, K. E., et al. 2015, in prep
Wolfire, M. G., et al. 2015, in prep