ALMA Observations of HCO\(^+\) and HCN Emission in the Massive Star-forming Region N55 of the Large Magellanic Cloud

Nayana A. J.\(^1\), Naslim N.\(^{1,2,3,8}\), T. Onishi\(^4\), F. Kemper\(^{2,5}\), K. Tokuda\(^{4,6}\), S. C. Madden\(^7\), O. Morata\(^5\), S. Nasri\(^1\), and M. Galametz\(^2\)

\(^1\) Department of physics, United Arab Emirates University, Al-Ain, 15551, UAE; naslim.n@uaeu.ac.ae
\(^2\) Academia Sinica Institute of Astronomy and Astrophysics, Taipei 10617, Taiwan, R.O.C.
\(^3\) Armagh Observatory, College Hill, Armagh BT61 9DG, UK
\(^4\) Department of Physical Science, Graduate School of Science, Osaka Prefecture University, 1-1 Gakuen-cho, Sakai, Osaka 599-8531, Japan
\(^5\) European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748, Garching b. München, Germany
\(^6\) National Astronomical Observatory of Japan, National Institutes of Natural Science, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
\(^7\) Laboratoire AIM, CEA/DSM—CEA Saclay, F-91191 Gif-sur-Yvette, France

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Abstract

We present the results of high spatial resolution HCO\(^+\)(1−0) and HCN(1−0) observations of the N55 south region (N55-S) in the Large Magellanic Cloud (LMC), obtained with the Atacama Large Millimeter/submillimeter Array (ALMA). N55-S is a relatively less extreme star-forming region of the LMC characterized by a low radiation field. We carried out a detailed analysis of the molecular emission to investigate the relation between dense molecular clumps and star formation in the quiescent environment of N55-S. We detect 10 molecular clumps with significant HCO\(^+\)(1−0) emission and 8 with significant HCN(1−0) emission, and estimate the molecular clump masses by virial and local thermodynamic equilibrium analysis. All identified young stellar objects (YSOs) in N55-S are found to be near the HCO\(^+\) and HCN emission peaks showing the association of these clumps with recent star formation. The molecular clumps that have associated YSOs show relatively larger line widths and masses than those without YSOs. We compare the clump properties of N55-S with those of other giant molecular clouds (GMCs) in the LMC and find that N55-S clumps possess similar size but relatively lower line width and larger HCN/HCO\(^+\)(1−0) flux ratio. These results can be attributed to the low radiation field in N55-S resulted by relatively low star formation activity compared to other active star-forming regions like 30 Doradus-10 and N159. The dense gas fraction of N55-S is ~0.025, lower compared to other GMCs of the LMC supporting the low star formation efficiency of this region.

Unified Astronomy Thesaurus concepts: Star formation (1569); Large Magellanic Cloud (903); Giant molecular clouds (653); Young stellar objects (1834); Interstellar molecules (849)

1. Introduction

Massive stars form as clusters in the densest clumps of giant molecular clouds (GMCs). These clumps are self-gravitating parsec-sized structures that collapse and fragment into dense cores to form high-mass stars (Williams et al. 2000). The physical processes that determine the fragmentation of GMCs to clumps and cores depend on the star formation history, cooling due to the buildup of metals, and feedback from massive stars. Different star-forming environments can change the properties of GMCs and its substructure. Thus, it is important to look at the GMCs and their substructure in different feedback environments to study star formation in galaxies.

Star formation studies on a galaxy-wide scale exist for the Milky Way (Kennicutt & Evans 2012). However, studying star formation in other galaxies is limited due to the lack of high-resolution instruments that can resolve the dense molecular clumps of GMCs. Such studies can be done in the Large Magellanic Cloud (LMC) due to its proximity. At a distance of 49.59 kpc (Nayak et al. 2016; Ambrocio-Cruz et al. 1998; Carlson et al. 2012), the presence of stellar cluster R136 and numerous OB stars makes 30 Doradus the most extreme star-forming GMC of the LMC (Pineda et al. 2009; Hughes et al. 2010; Nayak et al. 2016). N159 is also a region of intense radiation field \( \sim 156 \chi_0 \left( \chi_0 = 2.7 \times 10^{-3} \text{ erg s}^{-1} \text{ cm}^{-2} \right) \) (Draine 1978) and high turbulence and shocks (Nayak et al. 2018; Fukui et al. 2015). With only 11 identified OB stars (Olsen et al. 2001) and a radiation field of 18 \( \chi_0 \) (Pineda et al. 2009), N55 is an example of quiescent star-forming environment of the LMC.

N55 is a star-forming region of size \( \sim 60 \times 100 \text{ pc}^2 \) located in the supergiant shell GMC 4 (see Figure 1; Yamaguchi et al. 2001). While the bulk of LMC 4 is empty of ionized gas, N55 stands out as a bright H\,II region in the H\,O map (Olsen et al. 2001). The Spitzer observations of N55 show filamentary distribution of polycyclic aromatic hydrocarbon (PAH; Figure 1; Naslim et al. 2018). A total of 16 YSOs has been identified in the N55 from Spitzer photometric observations indicating ongoing star formation (Gruendl & Chu 2009; Seale et al. 2014). Naslim et al. (2015) detected the H\,2 rotational transitions at 28.2 and 17.1 \( \mu \text{m} \) in the N55 main molecular cloud complex with the infrared spectrograph on board Spitzer Space Telescope. Their studies shows a tight correlation of H\,2 surface brightness with the PAH and total infrared emission indicating photoelectric heating caused by UV radiation from massive stars. The \(^{12}\text{CO}(1−0)\) and \(^{13}\text{CO}(1−0)\) observations of N55 reveals the clumpy nature of molecular gas with a total mass of \( \sim 5.4 \times 10^4 \ M_\odot \) (Naslim et al. 2018).
CO isotopes probe molecular gas from relatively low-density regions (∼10² cm⁻³), whereas HCO⁺(1–0) and HCN(1–0) trace dense molecular clumps due to their high critical densities (∼10⁴ cm⁻³). In this paper, we present the HCO⁺(1–0) and HCN(1–0) observations of the main molecular complex towards the south of the N55 (hereafter N55-S; see Figure 1) with the Atacama Large Millimeter/submillimeter Array (ALMA). This is the first time HCO⁺ and HCN emission are observed toward N55. Our study aims to investigate the physical properties such as size, line width, mass, and dense gas fraction of the dense molecular clumps in a relatively quiescent region in the LMC. Seale et al. (2012) studied molecular clumps of different star-forming GMCs of the LMC (N159, N105A, N44, and N113) using the same dense gas tracers. A similar study was carried out by Anderson et al. (2014) in the 30 Doradus-10. Our work extends this sample including N55-S with a goal to explore how different star formation environments affect the properties of dense molecular clumps. We compare the physical properties and scaling relation of the dense molecular clumps of the N55-S with other extreme star-forming environments, mainly 30-Doradus (Anderson et al. 2014) and N159 (Seale et al. 2012).

The paper is organized as follows. We describe the ALMA observations and data analysis in Section 2 and present the regions of molecular emission in Section 3. The clump identification and physical properties of each clump are presented in Section 4. In Section 5, we inspect the spatial extent of dense gas tracers and CO isotopes to understand the density structure of the molecular cloud. We discuss the spatial coincidence of young stellar objects (YSOs) with the dense gas tracers and interpret the results in light of ongoing star formation in Section 6. Finally, we compare the properties of the molecular clumps of the N55 cloud with other GMCs of the LMC in Section 7. We summarize our results in Section 8.

2. ALMA Observations

The ALMA observations of N55 main molecular complex were carried out in cycle 3 (project code 2013.1.00993.S) on 2015 January 19. The observations were done with the ALMA 12m array in Band 3 in two frequency settings covering the HCN(1–0) and HCO⁺(1–0) lines at rest frequencies 88.6318 and 89.1885 GHz, respectively. The field of view of the observation is ∼3.5 × 2 arcmin², centered at R.A., decl. (J2000): 05:32:31.50; −66:26:22.5 covering ∼50 × 29 pc² in linear scale. Our observation is toward the southern region of N55 (N55-S) that covers the main molecular complex of N55 and does not cover the entire N55. The observations were carried out for a total integration time of 796 s. The correlator was set to have a bandwidth of 117.187 MHz split into 1920 channels in each spectral window. This corresponds to a native spectral resolution of 61 kHz (0.2 km s⁻¹). We binned the channels to a resolution of 0.4 km s⁻¹ for the analysis.

The data were reduced using the Common Astronomy Software Applications (CASA; McMullin et al. 2007) package. Uranus was used as the flux calibrator and J0526–6749 was used as the phase calibrator. The ALMA pipeline calibrated visibilities were imaged using CASA task TCLEAN with a channel resolution of 0.4 km s⁻¹. We applied the Briggs weighting with a robust parameter of 0.5. The achieved rms sensitivities per 0.4 km s⁻¹ channel for HCO⁺(1–0) and HCN(1–0) cubes are ∼10 and 11 mJy beam⁻¹, respectively. The synthesized beam of the HCO⁺(1–0) map is 4''07 × 3''11, which translates to a linear size of 0.98 × 0.74 pc² at the LMC distance. For the HCN(1–0) map, the synthesized beam is 4''13 × 3''14, which corresponds to 0.99 × 0.75 pc² in linear scale.

3. HCO and HCN Emission in N55

The velocity-integrated intensity maps of HCO⁺(1–0) and HCN(1–0) emission are shown in Figure 2. These maps are...
obtained by integrating the emission-line data cubes along the velocity axis. The maps show the clumpy nature of dense molecular gas in N55-S at parsec scales. The emission structures are mostly discrete, rather than nested or filamentary. A visual inspection suggests that the HCO\(^+\) (1–0) emission from each molecular clump originates from slightly extended regions as compared to HCN(1–0). This could be due to the higher densities probed by HCN(1–0) emission as compared to HCO\(^+\) (1–0). A similar trend in the spatial distribution of HCO\(^+\) (1–0) and HCN(1–0) emission in molecular clumps has been reported in the N105, N113, N159, and N44 regions (Seale et al. 2012). The positions of YSOs in the N55-S region identified by Spitzer observations (Gruendl & Chu 2009; Chen et al. 2009) are shown along with HCO\(^+\) (1–0) and HCN(1–0) clumps in Figure 2. The YSO positions are near the emission peaks of the clumps. The \(^{12}\)CO(1–0) and \(^{13}\)CO(1–0) maps of N55-S (Naslim et al. 2018) are also shown for a comparison that is discussed in Section 5.

4. Clump Identification and Characterization

We use astrodendro\(^9\) (a python package) to identify emission structures from the data cube. The algorithm identifies the hierarchical structure of emission (Rosolowsky et al. 2008).

Local maxima are identified from the data cube each with a flux >3\(\sigma_{\text{rms}}\), and the isosurfaces around the maxima are classified as leaves, branches, or trunks. If the isosurfaces do not have any substructures, they are categorized as leaves. The largest contiguous structures in the cube are identified as trunks. The structures intermediate to leaves and trunks are classified as branches. Thus, in a dendrogram, leaves do not overlap each other and they are the smallest emission clumps without substructures.

Astrodendro determines the basic parameters of the identified structures using the bisection method. The parameters are the velocity and positional centroids, integrated flux density, velocity dispersion (i.e., rms line width \(\sigma_v\)), rms sizes of the major \((\sigma_{\text{maj}})\) and minor \((\sigma_{\text{min}})\) axes of the clump, and the position angle of the major axis. For Gaussian line profiles, the FWHM line width (\(\Delta v\)) is given by \(\Delta v = \sqrt{8 \ln(2) \sigma_v}\). The spherical radius of the clump is \(R = 1.91 \sigma_r\), where \(\sigma_r = \sqrt{\sigma_{\text{maj}}^2 + \sigma_{\text{min}}^2}\). We use the bootstrapping technique to determine the uncertainties in the derived parameters.

We identify 10 significant molecular clumps in the HCO\(^+\) (1–0) and 8 in the HCN(1–0) data cubes. These are all identified as leaves by astrodendro. The properties of all these structures are listed in Table 1. For the resolution of our observations, we can resolve only clumps of size \(\geq 4''\). This translates to \(\sim 1\) pc at the LMC distance. The sizes of identified

\(^9\) http://www.dendrograms.org
Table 1
Details of the Clumps Identified by Astrodendo

| ID No. | R.A. (deg) | Decl. (deg) | $R$ (pc) | $\sigma_v$ (km s$^{-1}$) | $F_{\text{HCN}}/F_{\text{HCO}^+}$ | YSO Association |
|--------|------------|-------------|----------|------------------------|-------------------------------|------------------|
| 1      | 83.1406    | -66.4551    | 0.56 ± 0.14 | 0.43 ± 0.10 | 0.78 ± 0.12 | No |
| 2      | 83.1374    | -66.4523    | 0.49 ± 0.15 | 0.86 ± 0.12 | 0.60 ± 0.08 | Yes |
| 3      | 83.1343    | -66.4541    | 0.48 ± 0.19 | 0.67 ± 0.13 | 0.77 ± 0.15 | Yes |
| 4      | 83.1560    | -66.4450    | 1.11 ± 0.07 | 0.62 ± 0.05 | 0.58 ± 0.07 | No |
| 5      | 83.1385    | -66.4617    | 0.68 ± 0.12 | 0.53 ± 0.09 | 0.51 ± 0.09 | No |
| 6      | 83.1244    | -66.4557    | 0.41 ± 0.19 | 0.48 ± 0.19 | 0.46 ± 0.17 | No |
| 7      | 83.0933    | -66.4601    | 0.79 ± 0.10 | 0.94 ± 0.07 | 0.54 ± 0.12 | Yes |
| 8      | 83.0955    | -66.4526    | 1.12 ± 0.07 | 1.02 ± 0.04 | 0.53 ± 0.08 | Yes |
| 9      | 83.1347    | -66.4592    | 0.85 ± 0.11 | 0.62 ± 0.07 | ... | No |
| 10     | 83.0821    | -66.4490    | 0.79 ± 0.10 | 0.54 ± 0.08 | ... | No |

Note. $R$ and $\sigma_v$ denote the radius and velocity dispersion of each clump derived from astrodendo. $F_{\text{HCO}^+}$ and $F_{\text{HCN}}$ are the flux densities of the HCO$^+$ (1−0) and HCN (1−0) clumps, respectively.

Clumps are 1–2.2 pc, except for one clump (clump id = 6) with size 0.82 pc. The sizes of the dense molecular clumps in the massive star-forming regions of the Milky Way are ~0.1 − 1 pc (Retes-Romero et al. 2017). Given the limit in our spatial resolution, the smallest detected molecular structures in the N55-S seem compatible with the Milky Way clumps.

We present HCO$^+$ (1−0) emission spectra of all 10 identified clumps of the N55-S in Figure 3. We assert that all detections are strong with HCO$^+$ (1−0) emission peaks detected with a minimum spectral signal-to-noise ratio of 4. We note an additional redshifted feature in the spectrum of clump 9, possibly due to any dynamical activity in this region. The HCN/HCO$^+$ flux ratio of the clumps ranges from 0.46 ± 0.17 to 0.78 ± 0.12 (see Table 1), indicating overall weaker HCN flux in N55-S compared to HCO$^+$. We use HCO$^+$ as the primary clump tracer and further investigate various clump physical properties.

4.1. Clump Column Density

The molecular column density of the HCO$^+$ (1−0) transition at frequency $\nu$ is obtained by the assumption of local thermodynamic equilibrium (LTE; Barnes et al. 2011; Mangum & Shirley 2015):

$$N = \frac{3h}{8\pi^2} \frac{Q_{\text{rot}}}{g_u} \frac{E_u}{kT_{\text{ex}}} \exp \left( \frac{h\nu}{kT_{\text{ex}}} \right) - 1 \int T_\tau \ dV. \quad (1)$$

Here $\mu_u$ is the electric dipole matrix element that can be defined as $\mu_u = S\mu^2$, where $S$ is the line strength and $\mu$ is the dipole moment. $Q_{\text{rot}}$ is the rotational partition function of the HCO$^+$ molecule,

$$Q_{\text{rot}} = \Sigma_i g_i \exp \left( - \frac{E_i}{kT_{\text{ex}}} \right), \quad (2)$$

where $g$ is the degeneracy of the corresponding rotational level. $E_u$ and $g_u$ denote the energy and degeneracy of the upper molecular level, respectively. $T_{\text{ex}}$ is the excitation temperature, and $\int T_\tau \ dV$ denotes the optical depth of the emission line integrated over the velocity range.

The radiative transfer equation in the Rayleigh–Jeans limit can be written as

$$T_p = (T_{\text{ex}} - T_{\text{bg}})(1 - e^{-\tau}). \quad (3)$$

Here $T_p$ is the peak brightness temperature of the emission line, and $T_{\text{bg}}$ is the background temperature taken to be 2.72 K. The excitation temperature ($T_{\text{ex}}$) can be precisely determined if we have multiple transitions of HCO$^+$, while our observation is limited to a single transition. The excitation temperature $T_{\text{ex}}$ of the cloud can also be estimated from optically thick $^{12}\text{CO}(1−0)$ transition. Naslim et al. (2018) determined the excitation temperature of the N55-S molecular cloud using the $^{12}\text{CO}(1−0)$ transition (see Figure 4 of Naslim et al. 2018). Their study shows that $T_{\text{ex}}$ values of $^{12}\text{CO}(1−0)$ range from 20 to 40 K in the N55-S. We assume $T_{\text{ex}} = 30$ K as the excitation temperature of the HCO$^+$ (1−0) clumps in the N55-S for further calculations. This value is consistent with the typical excitation temperature of molecular gas in massive clumps (Faúndez et al. 2004; Fontani et al. 2005). We obtain the peak optical depth ($\tau_p$) from the peak brightness temperature of each clump using the equation (Barnes et al. 2011)

$$\tau_p = -\ln \left[ 1 - \frac{T_p}{(T_{\text{ex}} - T_{\text{bg}})} \right]. \quad (4)$$

The peak brightness temperature $T_p$ and optical depth $\tau_p$ of each clump are tabulated in Table 2. The partition function $Q_{\text{rot}}$ of the HCO$^+$ (1−0) transition is 14.4 at $T_{\text{ex}} = 30$ K (Rohlf & Wilson 2004; Mangum & Shirley 2015). Substituting for $Q_{\text{rot}}$ and taking $\int T_\tau \ dV = \tau_p \int \phi \ dV = \tau_p \sqrt{2\pi} \sigma_v$, Equation (1) can be simplified as (Barnes et al. 2011)

$$N_p = 6.02 \times 10^{17} \tau_p \sqrt{2\pi} \sigma_v \text{ m}^{-2}. \quad (5)$$

Here, we assume the emission-line profiles, $\phi(V)$, to be Gaussian, and $\sigma_v$ denotes the velocity dispersion of the line in km s$^{-1}$. Assuming the relative abundance of HCO$^+$ to H$_2$ to be X = 10$^{-9}$ (Loren et al. 1990; Caselli et al. 2002; Lee et al. 2003; Garrod et al. 2008; Zinchenko et al. 2009), we derive the column density of molecular hydrogen ($N_{\text{H}_2}$). The estimated values of $N_{\text{H}_2}$ are tabulated in Table 2. Clumps that are truly at a higher $T_{\text{ex}}$ will have lower $N_p$ and vice versa. For $T_{\text{ex}} = 40$ K, the $N_p$ values of the clumps are ~28% lower compared to the values derived for $T_{\text{ex}} = 30$ K and ~39% higher for $T_{\text{ex}} = 20$ K.

4.2. Clump Volume Density

The H$_2$ volume density ($n_{\text{col}}$) of each clump can be calculated assuming that the physical depth of the source is...
The above equation provides an average volume density through the clump along the peak of the emission line. The derived clump volume densities range from $300 \pm 50$ to $4850 \pm 1630$ cm$^{-3}$ (Table 2). HCO$^+$(1$\rightarrow$0) is expected to be thermalized at a critical density of $n_{\text{crit}} \sim 3 \times 10^5$ cm$^{-3}$ (Barnes & Crutcher 1990). The HCO$^+$(1$\rightarrow$0) line emission toward all the clumps in our sample is excited well below the critical density.

4.3. Mass-surface Density

We estimate the total mass-surface density ($\Sigma_p$) of molecular clumps using the HCO$^+$(1$\rightarrow$0) column densities (Barnes et al. 2011)

$$\Sigma_p = \left( \frac{N_p}{X} \right) (\mu_{\text{mol}} m_{\text{H}_2}),$$

where $\mu_{\text{mol}}$ is the mean molecular weight in the gas that is taken to be 2.3 (Barnes et al. 2011). The calculated mass-surface densities of all identified clumps of N55-S are given in Table 2. The values of mass-surface density vary from $29 \pm 4$ to $290 \pm 41$ $M_\odot$ pc$^{-2}$.
4.4. Mass of Molecular Clumps

The masses of molecular clumps (M_{LTE}) are calculated from the derived HCO\(^+\)\((1\rightarrow0)\) column densities under the LTE assumption.

\[
M_{LTE} = \frac{N_p}{X}(\mu_{mol}m_H)\pi R^2.
\]  
(8)

We also determine the clump virial masses (Larson 1981; Solomon et al. 1987; Saito et al. 2006; Wong et al. 2006; Muller et al. 2010) using the equation,

\[
M_{vir} = 125M_\odot \frac{(5-2\beta)}{(3-\beta)}\Delta v^2R.
\]  
(9)

This equation is based on the assumption that clumps are spherical in shape with a radial power-law density profile of index \(\beta\), we assume \(\beta = 1\) (van der Tak et al. 2000). \(R\) is the clump radius in parsec and \(\Delta v\) is the FWHM of the emission line in km s\(^{-1}\). The \(M_{LTE}\) and \(M_{vir}\) masses of the clumps, as well as the virial parameter, \(\alpha = M_{vir}/M_{LTE}\), are tabulated in Table 2.

5. Physical Properties of Dense Molecular Gas

We investigate the physical properties of the dense molecular clumps of N55-S in the LMC, traced by ALMA observations of HCO\(^+\)\((1\rightarrow0)\) and HCN\((1\rightarrow0)\). In Figure 2, we compare the velocity-integrated intensity maps of \(^{12}\)CO\((1\rightarrow0)\) and \(^{13}\)CO\((1\rightarrow0)\) (Naslim et al. 2018) with HCO\(^+\)\((1\rightarrow0)\) and HCN\((1\rightarrow0)\) of the N55-S region. The spatial distribution of the emission from all four molecular transitions is broadly similar. The maximum intensity in all four emission maps comes from clumps 2 and 3. The \(^{13}\)CO\((1\rightarrow0)\), HCO\(^+\)\((1\rightarrow0)\), and HCN\((1\rightarrow0)\) emissions are not detected in regions of \(^{12}\)CO\((1\rightarrow0)\) emission. It is evident that \(^{12}\)CO\((1\rightarrow0)\) emission is more widely spread compared to \(^{13}\)CO\((1\rightarrow0)\), HCO\(^+\)\((1\rightarrow0)\), and HCN\((1\rightarrow0)\). The distribution of the HCO\(^+\)\((1\rightarrow0)\) and HCN\((1\rightarrow0)\) emissions is most compact. The projected spatial distribution of emission from multiple species reflects the density structure of the molecular clumps from surface to the interior.

5.1. Dense Gas Fraction

We estimate the H\(_2\) mass traced by \(^{12}\)CO\((1\rightarrow0)\) (Naslim et al. 2018) luminosities (\(L_{CO}\)) from the N55-S region using the equation (Wong et al. 2011)

\[
M_{H_2} [M_\odot] = 4.4 \frac{X_{CO} L_{CO}}{2.2 \times 10^{20} \text{cm}^{-2}(K \text{km s}^{-1})} (K \text{km s}^{-1} \text{pc}^2).
\]  
(10)

Here \(X_{CO}\) denotes the CO-to-H\(_2\) conversion factor that has a Galactic value, \(X_{CO} = 2 \times 10^{20} \text{cm}^{-2} \text{K}^{-1} \text{km s}^{-1}\) s (Strong et al. 1988; Bolatto et al. 2013). Both theoretical and observational studies suggest that the \(X_{CO}\) value increases with decreasing metallicity. However, a Galactic value can be approximated for environments with metallicities down to \(\sim 0.5 Z_\odot\). (Leroy et al. 2011; Bolatto et al. 2013; Pineda et al. 2017). Hence, we use \(X_{CO} = 2 \times 10^{20} \text{cm}^{-2} \text{K}^{-1} \text{km s}^{-1}\) in our calculation. Naslim et al. (2018) report a 30\% missing flux in the ALMA \(^{12}\)CO\((1\rightarrow0)\) emission maps. Accounting for this, the total H\(_2\) mass traced by \(^{12}\)CO\((1\rightarrow0)\) is \((2.59 \pm 0.01) \times 10^4 M_\odot\). The total H\(_2\) mass traced by HCO\(^+\)\((1\rightarrow0)\) is \((0.70 \pm 0.10) \times 10^4 M_\odot\) (sum of \(M_{LTE}/\text{FWHM}\) in Table 2). Thus, the dense gas fraction in the N55-S region is 0.025 ± 0.005. A higher value \(X_{CO} = 4 \times 10^{20} \text{cm}^{-2} \text{K}^{-1} \text{km s}^{-1}\) (Hughes et al. 2010) will further decrease the dense gas fraction to 0.013.

5.2. Low Volume Densities of Dense Gas Clumps

The volume densities of 10 identified clumps are in a range \((0.30 - 4.85) \times 10^5 \text{cm}^{-3}\) (Table 2). Since HCO\(^+\)\((1\rightarrow0)\) has a relatively high critical density \(\sim 3 \times 10^6 \text{cm}^{-3}\) (Barnes & Crutcher 1990), we would expect the bulk of HCO\(^+\)\((1\rightarrow0)\) luminosity to originate in thermalized star-forming cores. However, all 10 HCO\(^+\)\((1\rightarrow0)\) clumps in our samples show volume densities well below the expected critical density. We note that similar low volume densities are reported for Milky Way clouds from HCO\(^+\)\((1\rightarrow0)\) emission (Barnes et al. 2011). The authors report that 95\% of all massive clumps emit well below the critical density. A study of HCO\(^+\)\((1\rightarrow0)\) emission from multiple clouds of the LMC also suggests that the majority of
the clumps have volume densities\(^{10}\) well below the critical density of the \(J = 1 - 0\) line (Seale et al. 2012).

This could happen if HCO\(^{+}(1-0)\) is subthermally excited and not thermalized to the local H\(_2\) gas. Significant HCO\(^{+}(1-0)\) emission can arise at densities lower than the critical density of the line (Evans 1999; Shirley 2015; Kauffmann et al. 2017). Another possibility is a severe underestimation of optical depth of the emission line due to a small beam filling factor. The clump mass can be calculated assuming that the clump volume contains gas at the critical density of the HCO\(^{+}(1-0)\) transition (Barnes et al. 2011):

\[
M = 5.3 \times f \left( \frac{n_{cr}}{10^{11} \text{m}^{-3}} \right) \left( \frac{R}{\text{pc}} \right)^{3}.
\]

(11)

Here \(n_{cr}\) denotes the critical density of HCO\(^{+}(1-0)\), and \(f\) denotes the beam filling factor. Comparing the above derived mass with the cloud mass derived from LTE analysis yields \(f = (0.001 - 0.01)\) for the clumps in our sample. This low beam filling factor could result from a highly clumpy structure of molecular clouds or if the clumps are not well resolved.

\(^{10}\) We computed the volume densities from the \(M_{LTE}\) and \(R\) values from Table 2 of Seale et al. (2012).

5.3. \(M_{\text{vir}}\) versus \(M_{LTE}\)

The virial and LTE masses of N55-S clumps are \((0.96 - 12.16) \times 10^{2} \, M_{\odot}\) and \((0.43 - 4.29) \times 10^{2} \, M_{\odot}\), respectively (see Figure 4(a)). In order to examine whether these clumps are gravitationally bound, we inspect the virial parameter, \(\alpha = M_{\text{vir}}/M_{LTE}\) (Figure 4(b)). The average value of the virial parameter is \(2.6 \pm 1.2\). A few isolated clumps such as 4, 6, 7, 8, 9, and 10 are not likely to be gravitationally bound. The relatively high value of the virial parameter could be due to an underestimation of \(M_{LTE}\) in these region or due to dynamical impact of star formation.

5.4. Size–Line Width Relation

The size and line width of HCO\(^{+}(1-0)\) clumps follow a power law, \(\Delta v \propto R^{0.65 \pm 0.32}\) (Figure 4(c)). The size–line width relation of \(^{12}\)CO\((1-0)\) clumps of the N55 is \(\Delta v \propto R^{0.4}\) (Naslim et al. 2018). The size–line width power-law index is found to be in the range 0.46–0.78 for several dense gas tracers in the central molecular zone (CMZ) of the Milky Way (Shetty et al. 2012). The slope is found to be 0.6 in extragalactic clouds (Bolatto et al. 2008) and 0.5 in Milky Way clouds (Heyer et al. 2009). Thus, the size–line width power-law index of HCO\(^{+}(1-0)\) clumps of the N55-S is consistent with the CMZ, extragalactic, and Milky Way clouds.
6. Clump Association with YSOs

There exist extensive catalogs of YSOs in the LMC due to its proximity and the ability to observe the entire galaxy (Whitney et al. 2008; Gruendl & Chu 2009; Indebetouw et al. 2004; Chen et al. 2009, 2010; Ellingsen et al. 2010). This gives the advantage of positionally matching the YSOs with dense molecular clumps to study star formation and the associated dense gas. In Figure 2, we mark the position of YSOs in the N55-S (Chen et al. 2009; Gruendl & Chu 2009) on top of the velocity-integrated intensity maps of HCO$^+$(1−0) and HCN(1−0). All four identified YSOs in the N55-S are near the HCO$^+$(1−0) and HCN(1−0) emission peaks (near clumps 2, 3, 7, and 8). The positional offset between the emission peak and YSO position is $1.16^\circ, 1.21^\circ, 0.43^\circ$, and $1.69^\circ$ for clump 2, 3, 7, and 8, respectively. If the YSOs are randomly distributed, the probability of a YSO locating within $2^\circ$ of an emission peak is only 0.04%. However, all four of the identified YSOs are near the emission peaks indicating their positions are not from a random distribution and are related to the dense molecular clumps. The young stars form in the densest cores of the molecular clouds (Krumholz et al. 2010). The YSOs that are at a significant offset from the emission peak of the molecular clumps are expected to be slightly more evolved than those at the core. This hypothesis is observationally supported by the detection of maser emission (sign of the early phase of YSO evolution) in 80% of YSOs located close to the emission peaks of molecular clouds (Seale et al. 2012). Thus, the YSOs associated with clumps 2, 3, 7, and 8 in the N55-S are likely to be early in their evolutionary stage.

Gruendl & Chu (2009) suggest that the 8 $\mu$m magnitude of YSOs can be treated as a good proxy of the YSO mass based on the radiation transfer models on the spectral energy distribution (SED) of various YSOs. The YSOs with an 8 $\mu$m magnitude brighter than [8.0] are classified as massive YSOs. The infrared SED fitting of various YSOs in N44 and N159 shows a YSO mass of $8-15 M_\odot$ for 8 $\mu$m magnitudes $\sim$[8.76], [8.94], and [8.24]. The masses are $\sim$5–10 $M_\odot$ for an 8 $\mu$m magnitude $\sim$[10.17] (Table 7 of Chen et al. 2009). The 8 $\mu$m magnitudes of the YSOs associated with clumps 2, 3, 7, and 8 in the N55-S are $\sim$[8.24], [7.27], [10.19], and [8.76], respectively (Gruendl & Chu 2009). Thus, the YSOs associated with clumps 2, 3, and 8 are likely to be massive (8–15 $M_\odot$) and associated with clump 7 could be of mass $\sim$(5–10) $M_\odot$.

We compare the physical properties of the clumps in light of the presence/absence of YSOs. The molecular clumps with YSOs in our sample are relatively more massive than those without YSOs. The average mass of the YSO-associated clumps is $245\pm96 M_\odot$, whereas the average mass of clumps without YSOs is $\sim$103 $\pm$ 39 $M_\odot$. Similar lines of observational evidence are reported for various regions of the LMC (Seale et al. 2012; Naslim et al. 2018) and for the Milky Way molecular clumps (Hill et al. 2005). The clumps with mass-surface densities $\gtrsim73 M_\odot$ pc$^{-2}$ show YSO association in N55-S. The mass-surface density threshold of clumps for massive star formation is $\sim$501 $M_\odot$ pc$^{-2}$ and 794 $M_\odot$ pc$^{-2}$ for N159W and N159E, respectively (Nayak et al. 2018). The star formation threshold for 30-Doradus is $\sim$670 $M_\odot$ pc$^{-2}$ (Nayak et al. 2016). Thus, the mass density threshold of N159 and 30-Doradus is (6–10) times higher compared to N55-S. This could be due to the relatively less extreme star-forming environment of N55-S. The stronger radiation field in N159 and 30-Doradus is possibly preventing massive star formation at low mass-surface density in these regions.

We also find the velocity widths of YSO-bearing clumps to be systematically larger than those of non-YSO-associated clumps. The velocity widths of YSO-associated clumps are $\Delta v = 1.6 - 2.4$ km s$^{-1}$, whereas the clumps without YSOs are $\Delta v = 1.0 - 1.5$ km s$^{-1}$. The larger line widths could be indicative of turbulence due to YSO activity, indicating that YSOs affect the properties of dense molecular clumps. These results are consistent with the $^{13}$CO(1−0) and $^{12}$CO(1−0) studies of the N55 region (Naslim et al. 2018). Similar results are reported for the $^{12}$CO(2−1) study of 30-Doradus (Nayak et al. 2016), $^{12}$CO/$^{13}$CO observations of N159W/E (Fukui et al. 2019; Tokuda et al. 2019), and the HCO$^+$(1−0) study of several GMCs of the LMC (Seale et al. 2012).

7. Comparison of N55 Clump Properties with Other LMC Clouds

Seale et al. (2012) studied molecular clumps of different star-forming GMCs of the LMC (N159, N105A, N44, and N113) using dense gas tracers HCO$^+$(1−0) and HCN(1−0). The authors used Australia Telescope Compact Array (ATCA) observations with a spatial resolution of $\sim6\times7^\prime$ arcsec$^2$ ($\sim1.4\times1.7$ pc$^2$ in linear scale) and a spectral resolution of $\sim$0.2 km s$^{-1}$ (for N105 and N113) and 0.4 km s$^{-1}$ (N159 and N44). A similar study of dense gas tracers at same spatial resolution was carried out by Anderson et al. (2014) in the 30 Doradus-10 with a spectral resolution of 0.84 km s$^{-1}$. We examine the molecular clump properties such as size, line width, mass, and dense gas fraction of the N55-S region in comparison to other GMCs of the LMC in Figure 4.

The size of clumps in N55-S is comparable to the clumps of other GMCs (see Figure 4(c)). However, the line widths of the N55-S clumps are slightly small compared to other regions of the LMC (Seale et al. 2012; Anderson et al. 2014). The small line widths could be indicative of relatively less energetic environmental conditions in the N55-S. We compare the clump masses (both virial and LTE) of N55-S with other star-forming regions of the LMC (Seale et al. 2012) in Figure 4(a). The $M_{\text{vir}}$ and $M_{\text{LTE}}$ derived for N55-S clumps are systematically lower than other regions of the LMC. A few of the dense molecular clumps of N55-S are likely not in gravitational equilibrium.

The molecular gas mass traced by the HCO$^+$(1−0) clumps versus the dense gas fraction for N55-S and other GMCs (Seale et al. 2012; Anderson et al. 2014) in the LMC is shown in Figure 4(d). The dense gas fraction of N55-S is 0.025 ± 0.005, smaller than the fraction seen in other GMCs, 0.1–0.24. Dense gas fraction is crucial for massive star formation and is directly proportional to the star formation efficiency within a GMC (Krumholz et al. 2012; Lada et al. 2012). This suggests that N55-S has lower star formation efficiencies compared to other GMCs of the LMC. However, we note that different dynamical environments of galaxies and stellar feedback play a crucial role in setting massive star formation efficiency (Querejeta et al. 2019; Ochsendorf et al. 2017).

The HCN/HCO$^+$ flux ratios of molecular clumps in the N55-S range from 0.46 ± 0.17 to 0.78 ± 0.12. HCN and HCO$^+$ molecules possess similar rotational constants and electric dipole moments. Hence, the higher flux ratio can be attributed to the relative abundance. However, we note that a strong UV radiation field due to high star formation activity can enhance the HCO$^+$ abundance in active star-forming regions (Bayet et al. 2011; Mejierink et al. 2011). The HCN/HCO$^+$ flux ratio is found to be (0.1–0.5) for various LMC clouds.
(N105, N113, N159, and N44) by Seale et al. (2012) and ~0.2 for 30 Doradus-10 by Anderson et al. (2014) at similar spatial resolutions. Thus, N55-S clumps possess a relatively high flux ratio compared to other GMCs in the LMC, possibly due to the low radiation field compared to other GMCs.

There exist HCN/HCO\(^+\) flux ratio measurements of various LMC clouds using single-dish observations in the literature (Chin et al. 1997; Nishimura et al. 2016). These authors report the flux ratios in the range (0.5–0.7) for various molecular clouds of the LMC (N113, N44BC, N159HW, N214DE, and N159W). These numbers are slightly higher than their respective values at high spatial resolution (parsec scale; Seale et al. 2012; Anderson et al. 2014), as mentioned above. The flux ratio from single-dish observations reflect the chemical composition pattern averaged over a molecular cloud scale of 10–14 pc where the effect of local star formation activity is smeared out. The parsec-scale observations probe individual dense star-forming clumps and need not be same as the flux ratio averaged over 10–14 pc. The higher HCN/HCO\(^+\) ratios with single-dish data imply that the variation in abundance has a greater impact on the ratio than in density.

8. Summary

We present high spatial resolution observations of HCO\(^+\)(1–0) and HCN(1–0) of the N55-S region in the LMC. We aim to compare the the dense molecular clump properties of the N55-S with other active star-forming regions (N159 and 30-Doradus) in order to understand the effect of different feedback environments on dense molecular clumps. We detect prominent HCO\(^+\)(1–0) emission from 10 clumps and HCN(1–0) emission from 8 clumps. Our main results are the following:

1. The column density of H\(_2\) gas traced by HCO\(^+\)(1–0) emission in N55-S clumps is in the range \(N_{H_2} \sim (0.2–1.6) \times 10^{22} \text{ cm}^{-2}\). The LTE mass and mass-surface density of the clumps are in the ranges \(M_{\text{LTE}} \sim (0.4–4.3) \times 10^3 M_\odot\) and \(\Sigma_p \sim (0.3–2.9) \times 10^9 M_\odot \text{ pc}^{-2}\), respectively.

2. The volume density of H\(_2\) gas is in the range \(n_{\text{col}} \sim (0.3–4.9) \times 10^3 \text{ cm}^{-3}\), less than the critical density of the HCO\(^+\)(1–0) emission line suggesting that the clouds are either subthermally excited or have very small beam filling factors.

3. The size–line width relation of HCO\(^+\)(1–0) clumps follow a power law with index 0.65 ± 0.32, similar to CMZ, several extragalactic and Galactic clouds that are consistent with the \(^{12}\)CO clumps (Naslim et al. 2018).

4. All four identified YSOs in the N55-S region are in the vicinity of HCO\(^+\)(1–0) and HCN(1–0) emission peaks indicating the association of these dense clumps with recent star formation. The YSO-associated clumps have relatively larger line widths and masses compared to those without YSOs.

5. The total H\(_2\) mass traced by \(^{12}\)CO(1–0) and HCO\(^+\)(1–0) in the N55-S region is \(2.59 \times 10^4 M_\odot\) and \(0.70 \times 10^3 M_\odot\), respectively, indicating a dense gas fraction of 0.025 ± 0.005. The dense gas fraction of N55-S is lower compared to other GMCs (N105, N113, N159, N44, and 30-Doradus) of the LMC indicating a relatively lower star formation efficiency.

6. The HCN/HCO\(^+\) flux ratio of N55-S is in the range 0.46 ± 0.17 to 0.78 ± 0.12, slightly higher than the ratio (0.1–0.5) seen in other GMCs like N105, N113, N159, N44, and 30-Doradus (Seale et al. 2012; Anderson et al. 2014). We interpret this to be an effect of relatively low radiation field and star formation activity in N55-S.

7. The N55-S clumps possess systematically lower line widths compared to other GMCs of the LMC (Seale et al. 2012; Anderson et al. 2014). We also note that the YSO-associated clumps of N55-S show a mass-surface density \(\geq 73 M_\odot \text{ pc}^{-2}\) that is (6–10) times lower compared to N159 (Nayak et al. 2018) and 30-Doradus (Nayak et al. 2016).

Our study of the dense molecular clumps in N55-S suggests that YSOs can significantly affect the properties of dense molecular clumps by increasing the line widths of molecular emission. Compared to other GMCs in the LMC, the dense molecular clumps of N55-S show smaller line widths, lower dense gas fraction, larger HCN/HCO\(^+\), and a smaller threshold of mass-surface density with YSOs indicating relatively less active star formation.

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ORCID iDs

Nayana A. J. https://orcid.org/0000-0002-8070-5400
Naslim N. https://orcid.org/0000-0001-8901-7287
T. Onishi https://orcid.org/0000-0001-7826-3837
F. Kemper https://orcid.org/0000-0003-2743-8240
K. Tokuda https://orcid.org/0000-0002-2062-1600
S. C. Madden https://orcid.org/0000-0003-3229-2899
O. Morata https://orcid.org/0000-0002-5908-9543
M. Galametz https://orcid.org/0000-0002-0283-8689

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