Star Formation in the Seemingly Quiet GMC N159-S

1. Introduction

Despite significant progresses in understanding the physics involved with the formation of single stars, we still only have crude ideas about why a giant molecular cloud (GMC) forms clusters, distributed associations, or no stars at all. Clearly, the key properties of GMCs displaying various intensities of star formation must be explored observationally in more detail. When combined with knowledge of stellar content and energy feedback, it is possible to assess the relative importance of self-propagating, triggered, and spontaneous star formation, and going even further, estimate the star formation efficiency of a GMC. Studying young stellar objects (YSOs) in GMCs is one of the most direct ways to connect the causal relation between the initial conditions (gas) and the end products (stars).

With the unprecedented sensitivity provided by the mid-IR *Spitzer Space Telescope*, it is now possible to study YSOs in different interstellar, and even galactic environments, such as in the Magellanic Clouds. Studies show that YSOs are frequently found in molecular clumps at the edges of HII regions (e.g., M17; Povich et al. 2009), in the rims of superbubbles (e.g., N 44; Chen et al. 2009a), or in the peripheries of supergiant shells (e.g., Book et al. 2009). In the Large Magellanic Cloud (LMC), ours and other studies find a distinct preferential association of currently forming massive stars with ionized gas where (now main-sequence) massive stars formed in the last few Myr (Chen et al. 2009a,b). As demonstrated by the distribution of YSOs in N 159 (Figure 1), this trend is even stronger for YSOs at the highest mass end comparable to O-type stars, and as a matter of fact none were found in the GMC N 159-S (Johannsson et al. 1998), south of the bright HII region N 159. The differences between dense molecular gas in the relatively quiescent N 159-S and its very active neighbor N 159-W offer a very powerful laboratory in which to understand the star-forming potential of extragalacitc GMCs in general.

Unlike its neighboring GMC to the north that harbors numerous massive YSOs, N 159-S shows a puzzling deficiency of such objects in the mid-IR, despite the fact that it is more massive. Is N 159-S a very young cloud which is just being formed and has not had enough time to form massive stars, or are there processes at work preventing massive star formation, possibly rendering N 159-S a super-sized Taurus molecular cloud? *The presence or absence of dense massive cores as precursors of massive star formation would help to distinguish between these scenarios. Thus we propose to study the dense gas distribution of N 159-S with ATCA HCO^+ and HCN observations.*

2. The GMC N 159-S: a Taurus Molecular Cloud or on its Way to Form Massive YSOs?

Although of comparable size and twice the cloud mass of its northern neighbor GMC N 159-W (Johansson et al. 1998), N 159-S shows a much lower level of star formation activity. While N 159-W is associated with the bright HII region N 159, two young clusters NGC 2078 and NGC 2084, two sizable groups of candidate Herbig Ae/Be (HAeBe) stars and 14 massive YSOs with 7 of them being O-type, N 159-S is associated with only a few small faint HII regions, a small group of candidate HAeBe stars, and 4 B-type YSOs (Nakajima et al. 2005; Chen et al. 2009b). N159-S is also “dark” in the mid-IR – *Spitzer* MIPS 24, 70, and 160 μm images only show faint, patchy diffuse emission, indicating that *even if* there are massive YSOs, they have to be at such a very early evolutionary stage that they emit mostly at sub-mm or mm wavelengths, like those found in the Galactic infrared dark clouds.

The N 159-S and N 159-W GMCs do not exhibit obvious differences in their bulk gas properties. The $45''$-resolution ESO SEST data (Johansson et al. 1998) show that these two have comparable integrated intensities at ^{12}CO(1-0) as well as ^{13}CO(1-0). Unlike the CO properties, observations of HCO^+, a dense tracer which requires densities of $\sim 10^5$ cm^{-3} for excitation, show that N 159-S is $\sim 1/5$ as bright as N 159-W (Johansson et al. 1998). Unfortunately with a resolution of $45''$, corresponding to 11 pc at the distance of the LMC, it is not clear what causes the lower HCO^+ brightness in N 159-S. As demonstrated in Figure 2 a HCO^+ mosaic of N 159-W and N 159-E made with $5''$-resolution ATCA observations, the distribution of dense gas is highly clumpy, far from smooth. Thus, high-resolution observations are needed to distinguish whether the clumps in N 159-S are either not as massive as those in N 159-W and thus appear fainter in HCO^+, or whether there are fewer massive clumps and thus suffer more greatly in beam dilution. *The ATCA is the only telescope that is presently capable of this study.*

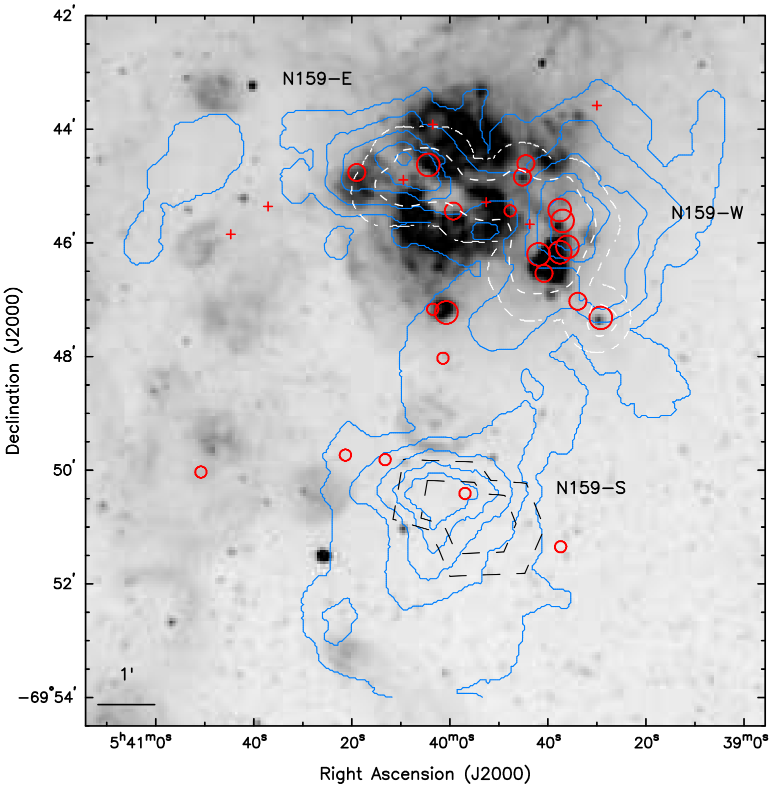

Figure 1: Distribution of YSOs on Hα image N 159. YSOs of different masses are marked as follows: large, medium, and small circles represent O, early B, and mid to late B, respectively, and pluses represent no estimate. Solid-line contours are from the ESO SEST CO mosaic and three GMCs are labeled (Johansson et al. 1998). The ACTA mosaic of N159 (Ott et al. 2008) and the proposed mosaic of N159-S are in white and black dashed lines, respectively. Inner and outer dashed lines indicate the 50% sensitivity contour of the mosaic and the outer bound of the observations.

The comparison between HCO^+ emission and the evolutionary stages of massive YSOs (Fig. 2) also reveals a correlation. The more evolved massive YSOs, as indicated by the dominant polycyclic aromatic hydrocarbon (PAH) emission and the lack of silicate absorption in the *Spitzer* IRS spectra (Seale et al. 2009), are not always associated with dense clumps. This is expected if the clumps have been dispersed by the energy feedback from the YSOs. However, the massive YSOs at early evolutionary stages, as indicated by the presence of deep silicate absorption in their IRS spectra, are *all* associated with dense clumps. Dense clumps therefore can be used as a diagnostic to search for massive YSOs at earliest evolutionary stages that do not emit significantly at mid-IR but at sub-mm and mms wavelengths. Such clumps, if found, can serve as finding charts for future Herschel observations to search for the protostars, as well as ALMA observations to examine the detailed kinematics of the clumps to assess whether there are signs of collapse.

3. Proposed Program

We propose simultaneous HCO^+ and HCN observations of N 159-S. The mapping area, composed of 15 pointings, is chosen to cover the core of CO map (the SEST 45″ HCO^+ also peaks there). In particular we concentrate on covering the regions that show 870μm emission, observed with LABOCA on APEX at 19″ resolution (Galametz, Hony, & Madden in preparation). Those submm-emitting regions are expected to have the greatest likelihood of containing dense clumps of molecular gas. We also cover regions where HAeBe stars and YSOs have been found (see Fig. 1), so are confident that our map will be a representative probe of star-forming gas in the GMC. Specifically, the proposed observations will be used to address the following three main issues:

• **What are the morphologies and masses of the dense gas in N 159-S?** Previous studies have shown that molecular clumps have similar mass functions as the stellar mass functions and that the clumps with higher masses are likely to form massive stars and clusters (Reid & Wilson 2005). We will identify the clumps, examine their spatial distribution, and estimate their masses. We will further compare the results to that of clumps in N 159-W, to examine how different the mass distribution is between these two GMCs such that they exhibit obviously different levels of star formation activity.

• **Is N 159-S a site that can or will form massive YSOs?** As shown in Figure 2, massive YSOs at early evolutionary stages are all associated with dense gas clumps. Detection of massive clumps would suggest that N 159-S may form massive YSOs in the future or the clumps may host massive YSOs at earliest stages. On the other hand, non-detection of massive clumps would indicate that N 159-S is less likely to form massive YSOs. Comparisons of morphologies and physical conditions such as velocity dispersions of these dense clumps to those associated with YSOs in N 159-W can shed light on the birth conditions of massive stars. The HCN/HCO^+ ratio can also used to examine how deep the UV radiation penetrates into the clumps, affecting chemistry and support against gravitational collapse via heating and increased ionization and magnetic coupling.

• **Are dense clumps coincident with dust emission?** As a massive protostar ages, the gas reservoir should be reduced near the protostar and the mass of the molecular gas clump should decrease. Indeed, Figure 2 shows that the HCO^+ peaks are more distant from YSOs that exhibit signs of more evolved evolutionary stages (Seale et al. 2009). We can begin to understand the distribution of remaining gas from the 870μm dust emission, and the molecular emission should *roughly* trace the dust. However, the molecular tracers offer several distinct advantages: the low-lying transitions will be more sensitive to the coldest and most quiescent clumps than the dust emission if the dust and gas temperatures are the same. If we find that those temperatures differ, that speaks directly to the radiation penetration, heating, and support of the clump. Finally, the kinematic information in linewidth and potential different sub-clouds is critical to understanding dynamics and star-forming potential.

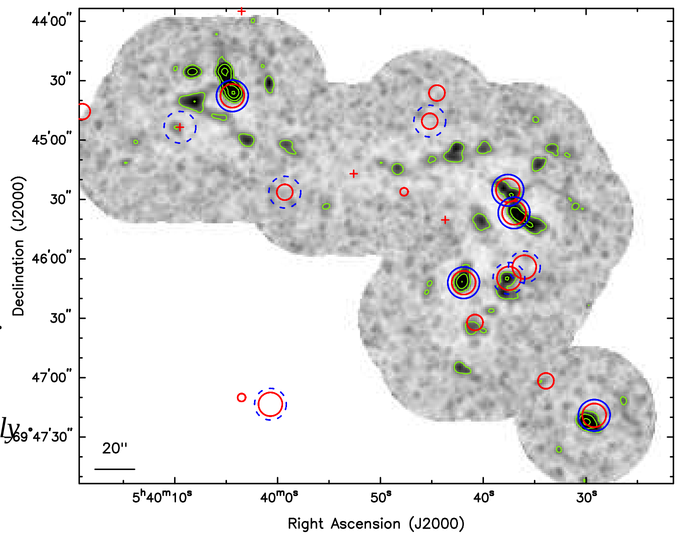

Figure 2: HCO^+ ATCA mosaic maps of N 159-W and N 159-E shown in grey scale and contours. Symbols are the same as Fig 1. Additional blue solid-line circles mark YSOs at early evolutionary stages as their IRS spectra show deep silicate absorption, and dashed-line circles for more evolved YSOs whose IRS spectra are dominated by PAH emission bands (Seale et al. 2009).

This program will help better understand star formation properties of a GMC and the physical conditions necessary for massive star formation, as well as search for sites of massive YSOs at their earliest stages for future detailed molecular studies with ALMA. The result will also provide insights on other GMCs with low star formation activities, such as the molecular ridge which is the largest gas concentration in the LMC (Indebetouw et al. 2008).

4. Time Request

To estimate the HCO^+ observation time, we use previous 9-pointing and 50-pointing mosaics of N 113 (project code CX145) and N 159 (C1544), respectively. For N 113, a sensitivity of 40 mJy bm^{-1} in a 0.5 km s^{-1} channel was achieved with a 5-hour integration time during a 10-hour observation, and similarly for N159. The ATCA Sensitivity Calculator estimates that with the newly-installed Compact Array Broadband Backend (CABB), the same sensitivity archived in N 113 and N 159 would require a 0.5-hour integration time for each pointing. We plan to observe HCN and HCO^+ in a single frequency band with a bandwidth of 2 GHz split into 2048 channels. This will give us channels of width ~ 3.5 km sec^{-1}. Allowing similar time for calibration as the previous observations, **but doubling the integration time to allow for potential detection of less massive clumps**, the proposed 15-pointing mosaic for the GMC N159-S requires a total of 30 hours of observation time.

5. References

Book, L. G., Chu, Y.-H., Gruendl, R. A., & Fukui, Y. 2009, AJ, 137, 3599; Chen, C.-H. R., et al. 2009a, ApJ, 695, 511; Chen, C.-H. R., et al. 2009b, ApJ, in preparation; Galametz, Hony, & Madden, A&A, in preparation; Gruendl, R. A. & Y.-H. Chu, 2009, ApJ, submitted; Indebetouw, R., et al. 2008, AJ, 136, 1442; Johansson, L. E. B., et al. 1998, A&A, 331, 857; Nakajima, Y., et al. 2005, AJ, 129, 776; Ott, J., et al. 2008, PASA, 25, 129; Povich, M. S., et al. 2009, ApJ, 696, 1278; Reid, M. A., & Wilson, C. D. 2005, ApJ, 625, 891; Seale, J. P., et al. 2009, ApJ, accepted