Observations of the Most Massive Deeply Embedded Star Clusters in the Milky Way

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Abstract  We summarize our comprehensive gas surveys of some of the most luminous, deeply embedded (optically obscured) star formation regions in the Milky Way, which are the local cases of massive star clusters and/or associations in the making. Our approach emphasizes multi-scale, multi-resolution imaging in dust and free-free continuum, as well as in molecular- and hydrogen recombination lines, to trace the multiple gas components from 0.1 pc (core scale) all the way up to the scales of the entire giant molecular cloud (GMC), or $\sim 100$ pc. We highlight our results in W49A, the most luminous Galactic star formation region ($L \sim 10^7 L_\odot$), which appears to be forming a young massive cluster (or a binary star cluster) with $M_\star > 5 \times 10^4 M_\odot$ that may remain bound after gas dispersal. The surveyed sources share elements in common, in particular, the 10-100 pc scale GMCs are filamentary but have one or two central condensations (clumps) far denser than the surrounding filaments and that host the (forming) massive stars.

1 Introduction

Young massive clusters (YMCs) have stellar masses $M_{cl} > 10^4 M_\odot$, scales of a few pc, and are younger than a $\sim 100$ Myr. They probably represent the young end of the so-called super star clusters (SSCs) found in starbursting galaxies [1, 2]. It is also possible that some of them are young analogues of globular clusters (GCs). Recent reviews are [3] and [4].

Understanding how YMCs form is key to understand the properties of star forming galaxies. Some studies have targeted the progenitor giant molecular clouds (GMCs) in nearby extragalactic systems [5, 6]. The deeply embedded, most luminous ($L > 10^6 L_\odot$) Galactic star formation regions stand out as the obvious candidates to be active local YMC formation sites [7]. These objects are rare in our Milky Way [8]. The evolution of their natal molecular clouds are governed by the interplay of gravity, turbulence, (proto-) stellar feedback, and potentially magnetic fields. The open questions to answer are: What are the properties and physical conditions of the molecular clouds that give birth to YMCs? What are the effects of YMC feedback upon its own parental cloud?

We are carrying a program to study in detail the GMCs of the most luminous star formation regions in the Milky Way. We emphasize multi-scale mapping using both

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interferometers and single dishes, both separately and combined. Here we highlight our first results in W49A, and compare to our previous results.

2 W49A

W49A is the most luminous star formation region in the Milky Way ($L \sim 10^{7.2} L_\odot$), embedded in one of the most massive giant molecular clouds (GMCs), $M_{\text{gas}} \sim 10^6 M_\odot$ [9]. The GMC has an extent of $l > 100$ pc, but all the prominent star formation resides in the central $\sim 20$ pc, and peaks in the subregion known as W49N. Part of the stellar population in W49N is already visible in the near-IR and its mass has been estimated at $M_{\text{cl}} \sim 4 \times 10^4 M_\odot$ [10], whereas the part associated with the most compact HII regions is not visible at wavelengths shorter than mid-IR.

We have performed extensive mapping observations of molecular lines toward W49A using the Submillimeter Array (SMA), the Purple Mountain Observatory 14m Telescope (PMO-14m), and the IRAM-30m Telescope [11]. The PMO-14m images with 3 pc resolution resolved several 10-30 pc scale radially converging gas filaments (Figure 1, left). The most active cluster-forming region W49N coincides with the convergence of these filaments. The two less prominent neighbors W49S and W49SW appear to be formed in the two densest gas filaments connecting to the southeast and southwest of W49N. The larger-scale filaments are clumpy.

Fig. 1 Mass surface density $\Sigma$ maps obtained from CO-isotopologue line ratios. The left panel shows the zoomed-out measurement from the PMO-14m telescope CO and $^{13}$CO 1–0 maps. The right panel shows the zoomed-in measurement from the SMA mosaics combined with IRAM-30m telescope maps of $^{13}$CO and C$^{18}$O 2–1. The embedded OB cluster-forming regions W49N, W49S, and W49SW are marked [11].

The combined IRAM-30m + SMA images with $\sim 0.1$ pc resolution further trace a triple, centrally condensed filamentary structure that peaks toward the central par-
sec scale ring of HC HII regions in W49N, which is known to host dozens of deeply embedded (maybe still accreting) O-type stars (Figure 1, right). In addition, localized UC HII regions are also found in individual filaments. Our finding suggests that the W49A starburst most likely formed from global gravitational contraction with localized collapse in a ‘hub-filament’ geometry.

From multi-scale observations of CO isotopologues, we derived a total molecular mass for the GMC $M_{\text{gas}} \sim 1.1 \times 10^6 M_\odot$ within a radius of 60 pc, and $M_{\text{gas}} \sim 2 \times 10^5 M_\odot$ within 6 pc [11]. Approximately $\sim 20\%$ of the gas mass in concentrated in $\sim 0.1\%$ of the volume. The mass reservoir is enough to form a YMC as massive as a globular cluster. Currently, only $\sim 1\%$ of the gas in the central few pc is ionized, which indicates that feedback is still not enough to significantly clear the GMC. The resulting stellar content might remain as a gravitationally bound massive star cluster or a small system of bound star clusters. Further analysis of this data is ongoing.

3 Other regions

Before our MUSCLE program in W49A [11] we have observed several other optically obscured, very luminous star formation regions to reveal the relation between the cloud to clump to core scales [12,13,14,15].

Figure 2 shows an early result in G20.08-0.04 ($L \sim 7 \times 10^5 L_\odot$), where velocity gradients interpreted as rotation are seen in dense gas tracers (NH$_3$ and CH$_3$CN) and infall is seen in NH$_3$ absorption against the background HC HII regions too. Both rotation and infall are seen at scales from $> 1$ pc (clump) to $< 0.1$ pc (core), indicating continuity in the accretion flow at multiple scales [12].

Figure 3 shows G10.6--0.4 ($L \sim 9 \times 10^5 L_\odot$). The similarities with W49A are striking, although scaled down. Filaments converge radially in a central hub which hosts most of the current OB star formation. The overall structure is hierarchical, with subfragmentations along the filaments which have further substructure.

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Fig. 2 Rotation in the dense gas at multiple scales in G20.08N. The left panel shows the parsec scale clump seen in NH$_3$ (3,3) emission. The star marks the position of the central HC_HII regions against which NH$_3$ is seen in absorption. The right panel zooms into the central 0.1 pc, where a similar velocity gradient is seen in denser, warmer gas traced by CH$_3$CN emission, although with less specific angular momentum [12].

Fig. 3 Large-scale mapping of G10.6–0.4. The central panel shows IRAM 30m and SMA 1.2-mm continuum emission. The inset shows the 30m+SMA mm image (blue contours) enclosing the ionized gas (yellow) of the central OB cluster [14].

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