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ALMA resolved views of molecular filaments/clumps in the Large Magellanic Cloud: A possible gas flow penetrating one of the most massive protocluster systems in the Local Group

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Abstract. We present spatially resolved molecular filaments and clumps in the high-mass star-forming regions N159E-Papillon, W-South, and W-North in the Large Magellanic Cloud (LMC). Our ALMA observations in CO isotopes and millimeter continuum revealed remarkable hub-filament systems with a typical width of 0.1 pc. The most massive clump in the observed regions, N159W-North MMS-2, shows an especially massive/dense nature whose total H_2 mass and peak column density are $\sim 10^4\,M_\odot$ and $\sim 10^{24}\,\mathrm{cm}^{-2}$, respectively, and harbors massive ($\sim 100\,M_\odot$) starless core candidates. The hub-filamentary clouds in the three regions share a common orientation and have 10–30 pc scale head-tail structures with active star formation at the tips. Their striking similarity proposes a "teardrops-inflow" model, i.e., substructured conversing H I flow, that explains the synchronized, extreme star formation across ∼50 pc, including one of the most massive protocluster clumps in the Local Group.

Keywords. Interstellar filaments, Large Magellanic Cloud, Protostars, Local Group

1. Introduction

The Large Magellanic Cloud (LMC) is an ideal laboratory to study high-mass star formation thanks to its uncontaminated face-on view at the closest distance (∼50 kpc) among the external galaxies. ALMA offers a fantastic opportunity to resolve the star formation mechanism at a $\sim 10^4$ au (0.06 pc) scale. N159E/W is an active high-mass star-forming region younger than $\sim 10^5$ years with the most intense CO emission among the molecular clouds discovered by the single-dish NANTEN survey (Fukui et al. 2008), where UV ionization by the stars has not yet dispersed the parental cloud as in R136. The tidal interaction between the LMC and the Small Magellanic Cloud (SMC) drove a kpc H I flow, which originated in the past close encounter between the two galaxies (Fukui et al. 2017; Tsuge et al. 2019). The N159 GMC may be the end product of a cloud strongly compressed by the H I flow and enriched to the large mass we observe currently.

2. ALMA observations toward N159 molecular clouds in the LMC

In ALMA Cycle 4, we carried out Band 6 (211–275 GHz) observations toward three massive star-forming regions, N159E-Papillon, N159W-South, and N159W-North. We

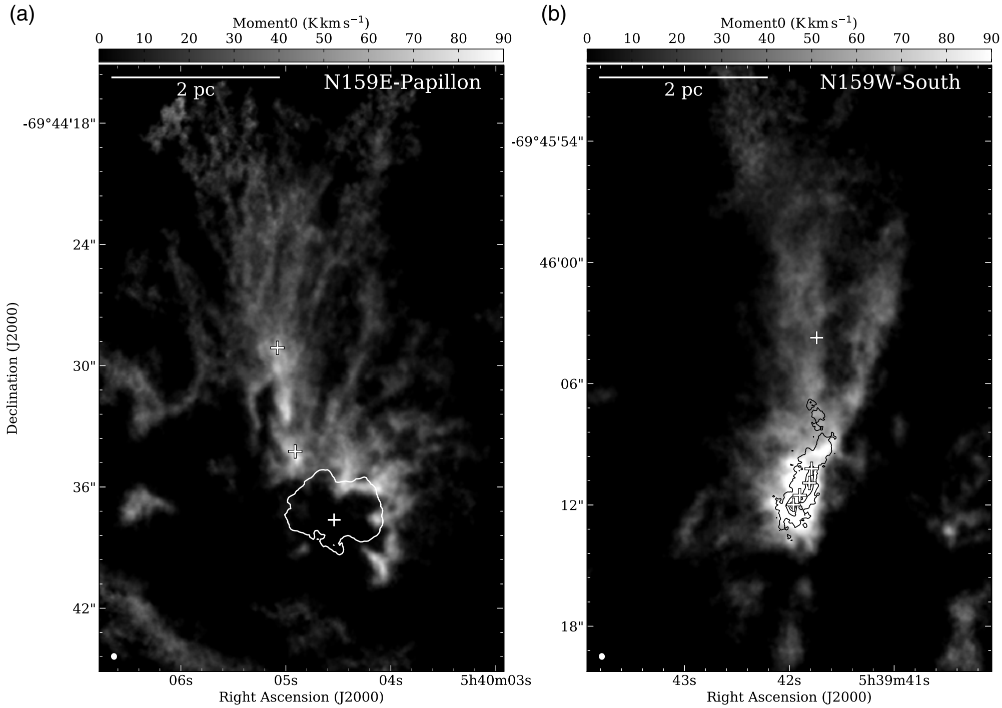

Figure 1. ALMA molecular cloud images toward the N159E-Papillon and N159W-South regions. (a) The grayscale image shows the ^{13}CO integrated intensity image. White contours show the Papillon Nebula H II region. White crosses represent high-mass protostellar sources. The white ellipse in the lower left corner shows the beam size. (b) Same as (b) but for the N159W-South region. Black contours show the 1.3 mm continuum emission.

selected the target regions based on our previous molecular cloud observations by Fukui et al. (2015) and Saigo et al. (2017). The frequency setting mainly targeted the molecular lines of ^{12}CO(2–1), ^{13}CO(2–1), C^{18}O(2–1), and the 1.3 mm continuum. The synthesized beam sizes of the molecular line and continuum images are $0.''27 \times 0.''23$ and $0.''26 \times 0.''23$, respectively.

2.1. *N159E-Papillon and W-South regions*

ALMA observations revealed remarkable hub-filament systems with a typical width of 0.1 pc in ^{13}CO, where a young H II region, the Papillon Nebula (see white contour in Figure 1a), and embedded high-mass protostars along with six protostellar outflows have been newly discovered/resolved (Figure 2). All these young protostellar objects have an age of 10^4 to 10^5 years, whereas they are scattered over a distance spanning ∼50 pc.

For N159E-Papillon (Figures 1a and 2a), the filamentary distributions are seen as "pillars" similar to those in the Galactic famous region, such as M16, extending into the Papillon Nebula. Although part of the filaments is already ionized in the H II region, the column density of the pillars is an order of magnitude higher than that of the pillars in M16.

Along the 1.3 mm continuum filament in N159W-South (Figure 2b), we performed the Gaussian fitting to the cross-section taken along the filament crest. The average width (FWHM) of the filament is ∼0.14 pc. The resultant line mass (=total mass/length) of the filament is $\sim 2 \times 10^3\ M_\odot\ \mathrm{pc}^{-1}$. These properties are consistent with those of "ridges" in Galactic high-mass star-forming clouds (e.g., NGC 6334, André et al. 2016). Note that

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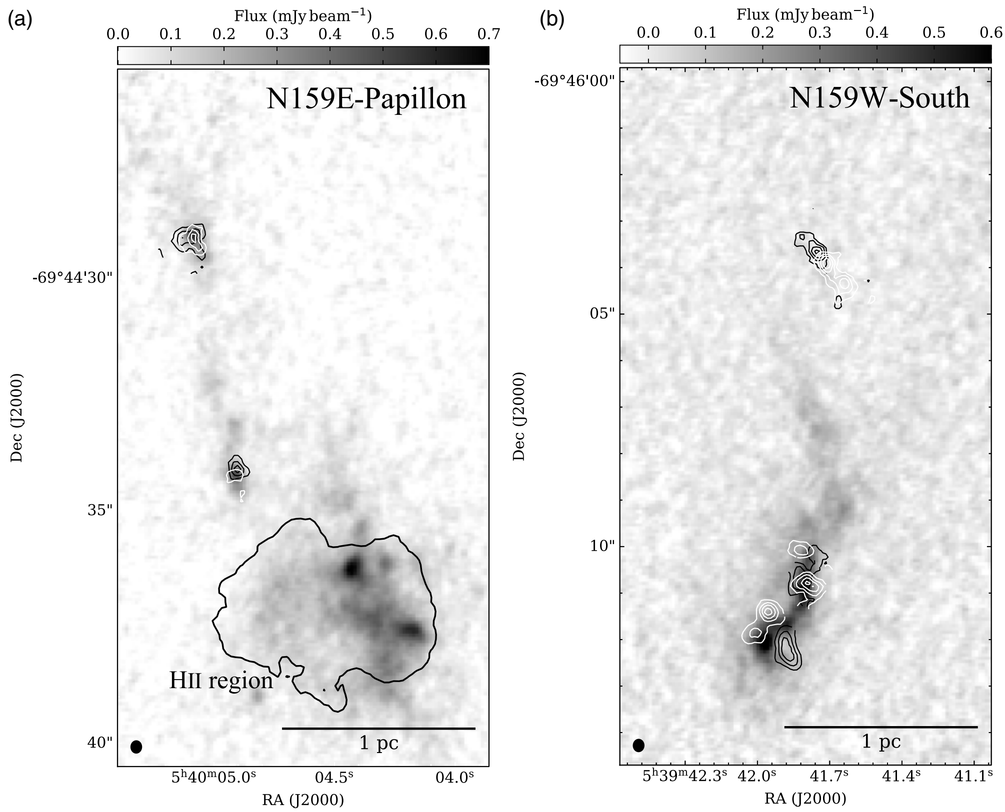

Figure 2. Millimeter continuum emission and ^{12}CO outflow distributions toward the N159E-Papillon and W-South regions. (a) The grayscale image shows the 1.3 mm continuum image. White contours show the Papillon Nebula H II region. Redshifted and blueshifted outflow lobes in ^{12}CO(2–1) are shown in white and black contours, respectively. The black ellipse in the lower left corner shows the beam size. (b) Same as (a) but for the N159W-South region.

the directions of the outflows are roughly perpendicular to the orientation of the ridge filament (Figure 2b).

2.2. *N159W-North region: One of the most massive prorocluster system in the Local Group*

The ^{12}CO and ^{13}CO high-resolution data depicted highly complex spatial and velocity structures of the N159W-North molecular cloud (Figure 3a). The ^{12}CO brightness temperature is higher than ∼30 K throughout the observed region and even higher than ∼50 K, especially on the southern side of the cloud (see "Warm side" in Figure 3a). One of the outstanding features is that several filaments, whose lengths and line masses are a few parsecs and ∼100 $M_{\odot}$ pc^{-1}, extend from high-mass star-forming dense cores toward the southern direction (Figure 3a).

Based on ^{12}CO high-velocity emission, which appears to be of outflow origin, we found five new bright star-forming cores in 1.3 mm continuum emission at the infrared quiescent spots. We also identified ∼0.1 pc scale starless cores with a mass of ∼100 $M_{\odot}$ that were not discovered in the previous extragalactic studies (Figure 3b). The dense molecular region (main ridge) traced by the thermal dust continuum and C^{18}O harbors the abovementioned proto- and prestellar cores. The total mass of the cluster-forming clump

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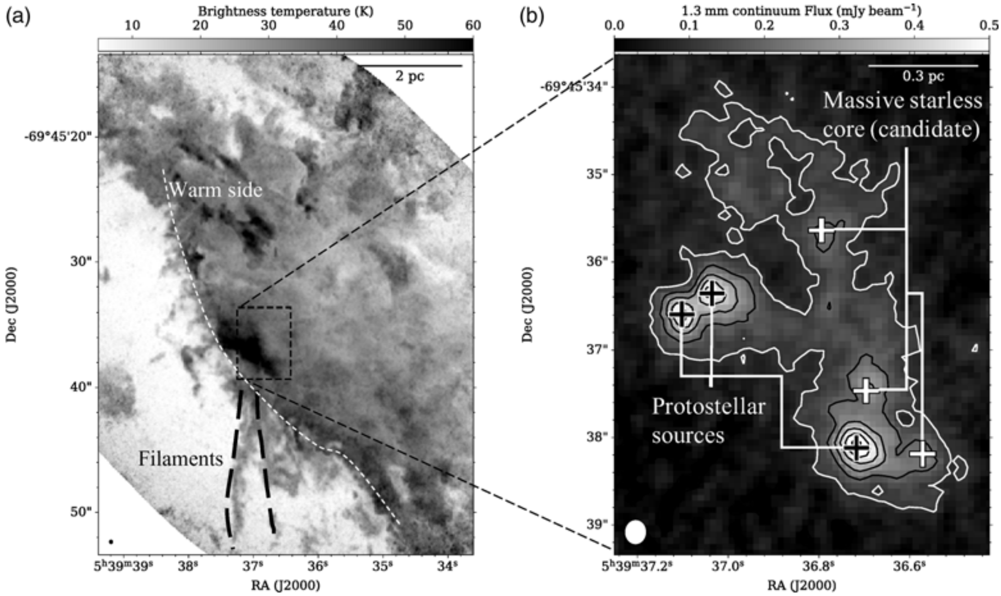

Figure 3. (a) Explanatory map of distinct features (see the text) in the N159W-North region on the high-resolution ^{12}CO(2–1) peak brightness temperature image. The black ellipse in the lower left corner gives the beam size. (b) The grayscale image and contours show an enlarged view of the 1.3 mm continuum emission toward MMS-2. The white ellipse in the lower left corner shows the beam size.

exceeds $10^4\,M_\odot$ despite its compact size of a few parsecs, making it one of the most massive, dense categories in the Local Group of galaxies (Tokuda et al. 2022 and references therein).

We investigated an archival CO(1–0) data set with a larger field of view and found a conical-shaped, ∼30 pc long complex extending toward the northern direction. These characteristics qualitatively resemble those of the V-shaped or head-tailed filaments in the N159E-Papillon and N159W-South regions.

3. Discussion

The line mass of the filaments in the three regions is as large as $\sim$ a few $\times\,10^2$–$10^3\,M_\odot\,\mathrm{pc}^{-1}$. Such supermassive filaments should be in a "supercritical″ and are considered to fragment and radially collapse within the freefall time. We speculate that the massive filaments that we see in the present observations formed quite recently and may be gravitationally unstable objects. Large-scale conversing flow is a promising trigger in the rapid formation of multiple filamentary complexes across more than 50 pc. A recent H I study by Fukui et al. (2017) suggested that kiloparsec-scale triggering of star formation occurred about 1 Myr ago through the compression in the converging H I flows in the R136-N159 region (Section 1). We suggest that the H I converging flows possibly triggered the coeval formation of three systems in N159. The formation of the filaments driven by the collision between two clouds is consistent with the magnetohydrodynamic simulations by Inoue et al. (2018), which show a hub-filamentary distribution with a pivot at the O-star formation site. The present picture explains the similar filamentary morphology of N159E and N159W, both of which show unevenly extended filaments to the north despite the large separation. The separation does not allow communication between the two nearly coeval star-forming spots within the O-star formation timescale of less than ∼1 Myr.

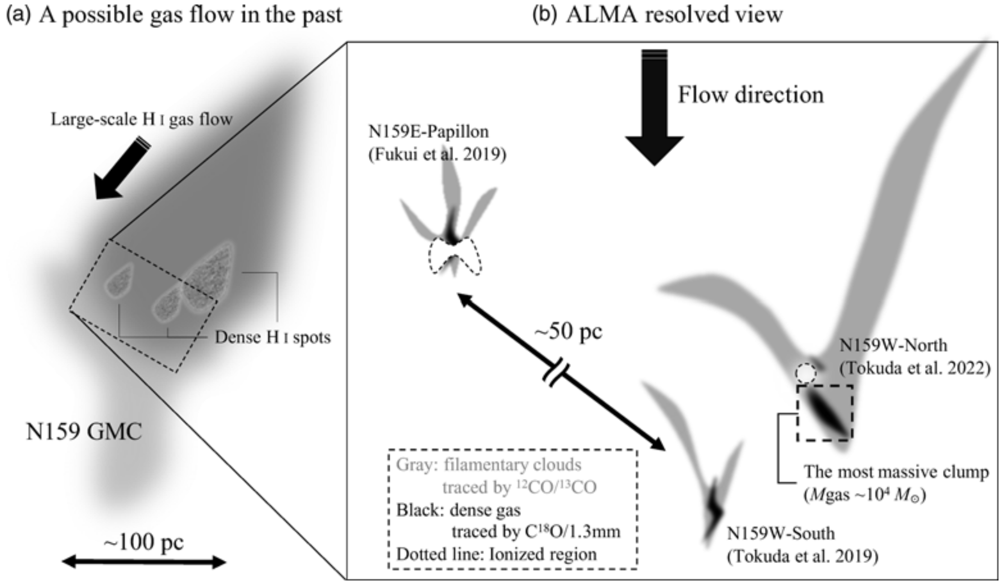

Figure 4. Schematic view of the star formation process in N159E/W motivated by the ALMA studies (see also Tokuda et al. 2022).

Combining our current observational understanding of N159E/W, three systems across more than 50 pc show active star formation simultaneously. Massive clumps, especially N159W-North-like objects (see Section 2.2), are highly rare in the Local Group, indicating that a typical galactic environment cannot easily produce YMC precursors. We hypothesize a "teardrops inflow model" (Figure 4) to explain the synchronized extreme cluster formation possibly driven by a quite dynamic, substructured flow induced by a galactic-scale phenomenon.

3.1. *Bibliography*

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