KINEMATIC STRUCTURE OF MOLECULAR GAS AROUND HIGH-MASS YSO, PAPILLON NEBULA, IN N159 EAST IN THE LARGE MAGELLANIC CLOUD: A NEW PERSPECTIVE WITH ALMA

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ABSTRACT

We present the ALMA Band 3 and Band 6 results of $^{12}$CO(2-1), $^{13}$CO(2-1), H30α recombinant line, free-free emission around 98 GHz, and the dust thermal emission around 230 GHz toward the N159 East Giant Molecular Cloud (N159E) in the Large Magellanic Cloud (LMC). LMC is the nearest active high-mass star-forming face-on galaxy at a distance of 50 kpc and is the best target for studying high-mass star formation. ALMA observations show that N159E is the complex of filamentary clouds with the width and length of ~1 pc and several parsecs. The total molecular mass is $0.92 \times 10^4 M_\odot$ from the $^{13}$CO(2-1) intensity. N159E harbors the well-known Papillon Nebula, a compact high-excitation HII region. We found that a YSO associated with the Papillon Nebula has the mass of $35 M_\odot$ and is located at the intersection of three filamentary clouds. It indicates that the formation of the high-mass YSO was induced by the collision of filamentary clouds. Fukui et al. reported a similar kinematic structure toward two YSOs in the N159 West region, which are the other YSOs that have the mass of $\gtrsim 35 M_\odot$. This suggests that the collision of filamentary clouds is a primary mechanism of high-mass star formation. We found a small molecular hole around the YSO in Papillon Nebula with a sub-parsec scale. It is filled by free-free and H30α emission. The temperature of the molecular gas around the hole reaches ~80 K. It indicates that this YSO has just started the destruction of parent molecular cloud.

Key words: ISM: clouds – ISM: kinematics and dynamics – ISM: molecules – stars: formation

1. INTRODUCTION

High-mass stars vastly affect the surrounding environments throughout their lifetime, which results in a rapid dissipation of the natal molecular clouds or, sometimes, in triggering the next-generation star formation. They are thus essential ingredients controlling the evolution of molecular clouds in spite of the orders-of-magnitude rareness compared to the lower-mass stars. The formation mechanism of high-mass stars has been largely unknown due to the rapid destruction of the parental clouds by stellar feedback. In theory, two high-mass star formation models have been under study for over 15 years (Zinnecker & Yorke 2007; Tan et al. 2014). The first one is the scale-up version of the low-mass star formation. The high-mass star is formed by the monolithic collapse of a gravitationally unstable massive molecular core (the so-called “Core Accretion Model”). The other one is that the forming low-mass star(s) gain the mass to become high-mass star(s) by the competitive mass accretion (Bonnell et al. 2004) as reviewed in recent articles (the so-called “Competitive Accretion Model”). In both models, the mass accretion on the high-mass star must overcome the radiative pressure and the ionization caused by the forming high-mass protostar (Nakano et al. 2000; McKee & Tan 2002; Yorke & Sonnhalter 2002; Hosokawa & Omukai 2009; Krumholz et al. 2009).

The importance of physical interactions between the molecular clouds, cloud–cloud collisions, has been recently addressed by many observational and theoretical studies as a mechanism of the formation of high-mass stars. NANTEN2 observations toward the super star clusters, Westerlund2, NGC 3603, and RCW 38, revealed supersonic collisions between two molecular clouds followed by strong shock compression of the molecular gas, leading to the formation of the massive clusters in a short time, less than 1 Myr (Furukawa et al. 2009; Ohama et al. 2010; Fukui et al. 2014, 2015b). Similar results were presented toward the single O star in M20 and RCW 120 (Tori et al. 2011, 2015). The theoretical study of collisions of dissimilar clouds was initiated by Habe & Ohta (1992), followed by Anathpindika (2010) and Takahira et al. (2014),...
indicating that the compression due to the collisions can produce massive molecular clumps. The magnetohydrodynamical numerical simulations by Inoue & Fukui (2013) have shown that the compression excites turbulence and amplifies field strength, leading to increased Jeans mass and a top-heavy dense-core mass function after collision, which explains the high-mass accretion rate required to form a high-mass star.

Recently, ALMA opened the possibility to observe molecular clouds in the external galaxies in a spatially resolved sense with the unprecedented angular resolution and sensitivity. Among the galaxies, the Large Magellanic Cloud (LMC) has been considered to be one of the best sites to study high-mass star formation. The LMC is close to us at a distance of 50 kpc (Schaefer 2008; de Grijs et al. 2014) and the inclination is almost face-on (Balbinot et al. 2015), which can minimize the effect of the contamination of various objects in the same line of sight. The star-formation activities in the LMC are quite high as shown by the existence of H II regions including 30 Dor, the largest one in the Local Group. Among a sample of nearly 300 Giant Molecular Clouds (GMCs) detected by NANTEN (Fukui et al. 1999, 2008; Mizuno et al. 2001; Yamaguchi et al. 2001, see also Fukui & Kawamura 2010), N159 is the H II region with the strongest CO intensity, with a total molecular mass of \(5.3 \times 10^5 M_\odot\). N159 is resolved into three prominent clumps; N159 West (N159W), associated with compact H II regions, N159 East (N159E), with developed H II regions, and N159 South (N159S), which is not associated with H II regions (Mizuno et al. 2010). The two clumps showing currently active star formation, N159W and N159E, have been observed by ALMA in Cycle 1, and the results of N159W were presented by Fukui et al. (2015).

Mizuno et al. (2010) suggested that the N159W peak represents a pre-star-cluster clump of \(\sim 10^5 M_\odot\) from observations in multiple-J rotational transitions of CO at a 10 pc resolution. By using ALMA, Fukui et al. (2015) spatially resolved the molecular gas in N159W with a spatial resolution of 0.3 pc \(\times\) 0.2 pc in \(^{12}\)CO(2-1) and \(^{13}\)CO(2-1), and found that the distribution is highly filamentary with a large clump (N159W-N) toward the N159W peak in the past observations. These filamentary clouds show straight or curved distributions with a typical width of 0.5–1.0 pc and a length of 5–10 pc. They also detected molecular outflows toward two high-mass protostars (YSO-N and YSO-S in their paper) for the first time in the external galaxies, showing that these protostars are quite young with an estimated dynamical timescale of \(\sim 10^4\) years. Impressive, in particular, is N159W-S, one of the outflows that is located at the intersection of two spatially overlapping filaments. Based on the results, they argued that the two filaments collided with each other and triggered the formation of the high-mass star YSO in N159W-S (YSO-S) in a short timescale of \(\sim 10^3\) years.

Following Fukui et al. (2015), it is of high importance to look at the neighboring star-forming region, N159E, which is associated with several developed H II regions and molecular clouds, which are observed as dark lanes in optical and H\(\alpha\) images (Mizuno et al. 2010), and to explore how star formation is influenced by cloud motion and distribution in N159E, where the “Papillon Nebula” is an intriguing unique compact H II region (Heydari-Malayeri et al. 1999; Meynadier et al. 2004). In addition, Chandra observations revealed a large X-ray bubble toward the largest H II region, which is considered to represent supernova remnants (Seward et al. 2010), suggesting that the molecular gas may be affected by the past explosive events.

In this paper, we present the results of ALMA observations of molecular clouds in N159E. The focuses will be on the filamentary distribution of the molecular clouds and the formation of the high-mass star “Papillon Nebula,” and a comparison with N159W will broaden and deepen our understanding of the evolution of GMCs in the LMC. We describe observations in Section 2 and results including YSO properties in Section 3. We then discuss the triggering of high-mass star formation in Section 4 and conclude the paper in Section 5.

2. OBSERVATIONS

We carried out ALMA Cycle 1 Band 3 (86–116 GHz) and Band 6 (211–275 GHz) observations toward N159E, both with the main array 12 m antennas and the Atacama Compact Array (ACA) 7 m antennas. This observation is based on ALMA High Priority Project 2012.1.00554.S (PI: Yasuo Fukui). This project consists of mapping observations of the N159E and N159W molecular clumps in LMC, using the same observational setting (spectral setting, spatial resolution, and sensitivity). Results of N159W, which is the counterpart result of this paper, are shown by Fukui et al. (2015). For N159E, we have observed the main body of the molecular clump in N159E region by using the mosaic mapping of the 60” \(\times\) 75” rectangular region around the central position of \((\alpha_{2000.0}, \delta_{2000.0}) = (05^h 40^m 08^s 0429, -69^\circ 14^\prime 59^\prime 515)\). Our target molecular lines were \(^{13}\)CO\((J = 1-0)\), \(^{13}\)CO\((J = 2-1)\), \(^{12}\)CO\((J = 2-1)\), \(^{13}\)CO\((J = 2-1)\), and \(^{18}\)O\((J = 2-1)\) with the frequency resolution of 15.3 kHz \((\times 3840\) channels). We also observed the continuum emission with the wide bandwidth of 1875.0 MHz (488.3 kHz 3840 channels). The radio recombination lines (RRLs) of H3\(\alpha\) and H4\(\alpha\) were included in the wide bandwidth observations. The ALMA Band 6 observations were carried out on 2013 December 2 and 2014 March 7 with a total on-source time of 25 minutes. It used 27 antennas, and the projected baseline length of the 12 m array range is from 13 to 392 m. The ALMA Band 3 observation was carried out on 2013 December 3 with a total on-source time of five minutes. It used 26 antennas and the projected baseline length of the 12 m array range is from 15 to 452 m. In both Bands, projected baselines of ACA observation cover from 8 to 36 m.

In calibration processes, we made additional flagging of a few antennas for which the gain is too low or show large amplitude dispersion in time. The bandpass calibration of the 12 m array was carried out by using four quasars (J1058+0133 and J0538–4405 in Band 6 and J0067–7516 and J0334–4008 in Band 3). The complex gain calibration was carried out by using three quasars (J0635–7516 and J0601–7036 in Band 6 and J0635–7516 in Band 3). These quasars have sufficient flux densities for the calibration. Flux calibration was carried out by using three solar system objects (Pallas and Ganymede in Band 6 and Uranus in Band 3). For the flux calibration, we used the Butler-JPL-Horizons 2012 model (https://science.nrao.edu/facilities/alma/aboutALMA/Technology/ALMA Memo Series/alma594/abs594). The calibration reduction were made using the Common Astronomy Software Application package (http://casa.nrao.edu) and visibility imaged. We used the natural weighting for both the Band 6 and Band 3 data, providing synthesized beam sizes of...
3. RESULTS

3.1. Filamentary Distribution of Molecular Gas toward N159E in 12CO(2-1) and 13CO(2-1)

Figure 1 shows the velocity-integrated intensity image of N159E in 12CO(2-1) and 13CO(2-1) obtained with the 12 m array of ALMA. The total fluxes of 12CO(2-1) emission with the 12 m array and with the 7 m array are almost the same with a difference of less than 10%, and thus we use only the 12 m array data here because no significant resolved-out emission is expected due to the interferometric observations. Figure 1(a) shows that molecular clouds are distributed throughout N159E and the prominent feature is three belt-like structures extending from the northeast to the southwest with lengths of 10–20 pc. These cloud complexes are resolved into smaller scale filamentary/clumpy features. Many of them are also traced by the denser gas tracer, 13CO(2-1) emission (see Figure 1(b)).

We estimated the mass and column density of the N159E cloud using two different methods. The total mass is estimated to be \((1.3 \pm 0.4) \times 10^6 M_\odot\) from the 12CO(2-1) intensities by the same method as in Fukui et al. (2015). In this estimation, we assumed the typical 12CO(2-1)/12CO(1-0) ratio toward H II regions of 0.85 (the ratio in the Orion-KL region of Nishimura et al. 2015) and a conversion factor from the 12CO(1-0) intensity to the column density of \(X(\text{CO}) = (7 \pm 2) \times 10^{20} \text{ cm}^{-2}\) (Fukui et al. 2008). The detection limit of the column density is \(\sim 2.0 \times 10^{21} \text{ cm}^{-2}\) and the maximum column density is \(\sim 2.0 \times 10^{23} \text{ cm}^{-2}\). The mass estimation from the 12CO intensity may be inaccurate in the optically thick region of the high column density or the heated cloud by the high-mass star (see Section 3.3). Thus, we estimated the mass also from 13CO(2-1) intensity by assuming the local thermodynamical equilibrium and the 13CO/H2 abundance ratio of \(3.2 \times 10^{-7}\) (Fujii et al. 2014). Fujii et al. (2014) assumed a uniform excitation temperature of 20 K, because the large beam size diluted the line intensities, hampering the estimation of absolute peak temperatures; the present ALMA observations spatially resolved the molecular distribution. The excitation temperatures were thus calculated from the peak 12CO(2-1) temperature by assuming that the line is optically thick, and were assumed to be 20 K, where the calculated excitation temperatures were below 20 K (e.g., Nishimura et al. 2015).

The total molecular mass of N159E in the present map is then calculated to be \(0.92 \times 10^6 M_\odot\) from the 12CO(2-1) intensity. It is consistent with the mass derived from 12CO(2-1).

White cross and dot symbols denote the position of four high-mass YSO candidates, which are cataloged in Gruendl & Chu (2009), Chen et al. (2010), and Carlson et al. (2012). The strongest CO intensity clump of 12CO(2-1) and 13CO(2-1) is associated with the high-mass YSO, J054009.40-694437.6, which is pointed as a large cross symbol. This YSO is also associated with a compact H II blob called the Papillon Nebula (Heydari-Malayeri et al. 1999; Meynadier et al. 2004; hereafter, we call it “Papillon Nebula YSO” in this paper). The high-mass YSO candidate, J054009.49-694453.5, is located at a local peak of the molecular cloud. Two white dot symbols denote the position of newly identified high-mass YSO candidates by Carlson et al. (2012). They are not clearly associated with the dense molecular cloud but still possess remnant circumstellar material (see details in Section 3.2).

Figure 2 shows Hα and CO intensity distributions toward the N159 cloud. The color image shows the Hα intensity distribution based on observations made with ESO telescopes at the La Silla Observatory programme ID 07.C-0888; processed and released by the ESO VOS/ADP group with the logarithmic scale (see Mizuno et al. 2010). The gray contour shows the integrated intensity of 12CO(2-1) with the ASTR 10 m telescope (Minamidani et al. 2008).
Figure 2. Hα image and CO integrated intensity toward the N159. Black and gray contours show the integrated intensity map of $^{12}$CO ($J = 2-1$) with ALMA Band 6 and $^{12}$CO ($J = 3-2$) with the ASTE 10 m telescope, respectively. The black dotted contour shows the mapping area of our ALMA Band 6 observation.

N159E and N159W cloud are located at the eastern and western edges of the N159 H II bubble. The black contours show the integrated intensity of $^{12}$CO ($J = 2-1$) toward N159E and N159W with ALMA Band 6 (see Fukui et al. 2015 for N159W) with the contour levels of 10 and 30σ (1σ = 0.3 Jy/Beam km s$^{-1}$). The ALMA mapping area of this observation is shown by the black dotted contours. The distribution of molecular cloud is coincident with the dark lane in the optical Hα image except for the southern part of N159W. Most of the high-mass YSO candidates, especially YSO candidates with masses of more than 30 $M_\odot$ (large cross symbols) are clearly associated with the molecular cloud. These results suggest that the main body of the molecular clouds is located in front of the N159 H II bubble and the destruction of the molecular cloud caused by the high-mass YSOs has not been progressed. Both regions are in the early stage of high-mass star formation and are in similar environments.

Figure 3 shows the velocity channel maps of the N159E cloud in $^{12}$CO(2-1) and $^{13}$CO(2-1). It shows that the N159E cloud consists of a large number of clumpy/elongated clouds with different velocities. The typical width and projection length of the elongated clouds are ~1 pc and 5 pc–10 pc, respectively, and we describe these elongated clouds as filaments in the present paper due to the high-aspect ratio. Many of the filaments are aligned roughly in the northeast–southwest direction. Some of the filaments that are associated with high-mass YSO candidates are in the north–south direction. In particular, filaments associated with the Papillon Nebula have a unique kinematic structure. We show the kinematic structure of the filaments associated with Papillon Nebula YSO in detail in Section 3.3.

3.2. YSO Characteristics

In recent years, nearly 2000 YSO candidates have been identified in the LMC using the near- to far-IR observations (Whitney et al. 2008; Gruendl & Chu 2009; Chen et al. 2010; Carlson et al. 2012; Seale et al. 2014) with a relatively small fraction of them confirmed as bona fide YSOs through follow-up spectroscopic observations (e.g., Shimonishi et al. 2008; Oliveira et al. 2009; Seale et al. 2009; van Loon et al. 2010). The photometric studies used the data from two LMC-wide surveys: the Spitzer Space Telescope “Surveying the Agents of Galaxy Evolution” (SAGE) survey (3.6–160 μm; Meixner et al. 2006) and the Herschel Space Observatory “HERschel Inventory of The Agents of Galaxy Evolution” (HERITAGE) survey (100–500 μm; Meixner et al. 2013) with spatial resolutions ranging from ~2′′ (Spitzer’s shortest wavelengths) to ~40′′ (the longest Herschel wavelength). Our ALMA Cycle 1 observations allow us to relate the properties of the YSOs identified in N159E and N159W to the properties of the molecular gas in which they reside.

There are four YSOs in our ALMA footprint of N159E (see Figure 2; Gruendl & Chu 2009; Chen et al. 2010; Carlson et al. 2012; Seale et al. 2014; Fukui et al. 2015). Table 1 lists physical properties of these sources reported in the literature (Chen et al. 2010; Carlson et al. 2012). These parameters were estimated using the spectral energy distribution (SED) fitting with the Robitaille et al. (2006) YSO radiative transfer models. Stellar masses ($M_*$,avg) and total luminosities ($L_*$,avg) are the average values calculated using stellar masses and total luminosities from “acceptable” fits; see Carlson et al. (2012) and Chen et al. (2010) for details. The first two objects in Table 1, also shown as crosses in Figure 1, are both high-mass...
YSOs with a significant amount of CO gas surrounding them. Both sources were classified as Stage I YSOs. The fitting results indicate that the Papillon Nebula YSO has a nearly pole-on orientation. The mass and luminosity are estimated to be \( \sim 19.7 M_\odot \) and \( \sim 5.3 \times 10^4 L_\odot \) for the Papillon Nebula YSO, and \( \sim 20.8 M_\odot \) and \( 6.3 \times 10^4 L_\odot \) for 054009.49-694453.5 (Chen et al. 2010).

Note that the mass estimation for the Papillon Nebula YSO using SED fitting suffers from large uncertainties. Chen et al. (2010) concluded that the Papillon Nebula YSO consists of multiple sources since the single-YSO model fails to reproduce the SED simultaneously using the flux between optical and mid-IR emission. This model fit is biased toward shorter wavelengths (\( \lambda < 8 \mu m \)) and it cannot reproduce the flux at longer wavelengths (see Figure 7 in Chen et al. 2010). Chen et al. (2010) also show that the mid-IR part of the SED can be reproduced by more massive models with \( M_\dot{\nu} \sim 41 M_\odot \). This may be a more plausible estimate of the YSO mass because it is consistent with the stellar mass derived from centimeter-wave radio observations by Indebetouw et al. (2004). In order to check the mass estimation, we also carried out the SED fitting using the same set of YSO models, but including the Herschel/HERITAGE photometry data from 100 to 500 \( \mu m \) (Meixner et al. 2013) in addition to optical and the infrared data from Chen et al. (2010) and we got similar results (\( M_\dot{\nu,avg} \sim 35 M_\odot \)) and thus we put this mass in Table 1. The Herschel fluxes were used as upper limits due to the much coarser resolution in

### Table 1

| Source Name \(^a\) | Other Name | \( M_\dot{\nu,avg} (M_\odot)^b \) | \( L_\dot{\nu,avg} (L_\odot)^b \) | Evol. Stage \(^c\) |
|-------------------|------------|------------------|------------------|----------------|
| 054004.40-694437.6 | Papillon Nebula YSO | 35 | (0.5–1.8) \times 10^3 | I | ... |
| 054009.49-694453.5 | ... | 20.8 ± 2.6 | (6.3 ± 1.6) \times 10^4 | I | 1 |
| J054000.68-694439.2 | ... | 11.2 ± 0.0 | (4.7 ± 0.0) \times 10^4 | I | 2 |
| J054005.26-694400.3 | ... | 9.5 ± 0.2 | (5.3 ± 0.5) \times 10^3 | I | 2 |

Notes.

\(^a\) “Source Names” from Carlson et al. (2012) are IRAC designations from the SAGE “IRAC Single Frame + Mosaic Photometry” Archive (Meixner et al. 2006); they begin with “SSTISAGEMA.” The names of the sources from Chen et al. (2010) come from Gruendl & Chu (2009).

\(^b\) \( M_\dot{\nu,avg} \) and \( L_\dot{\nu,avg} \) are the average stellar mass and total luminosity, respectively, calculated using stellar masses and total luminosities from “acceptable” fits; see Carlson et al. (2012) and Chen et al. (2010) for details.

\(^c\) The evolutionary “Stages” classification was defined in Robitaille et al. (2006) and is based on physical parameters. For Stage I sources \( M_\dot{\nu}/M_{\text{env}} < 10^6 \) year.

References. (1) Chen et al. (2010), (2) Carlson et al. (2012).
Figure 4. (a) Hα image of the Papillon H II region by WFPC2 of HST. The field size is 18 arcsec × 18 arcsec (4.5 pc × 4.5 pc). The white contour shows the integrated intensity of 12C(2-1). Contour levels start from 10σ in steps of 10σ (1σ = 0.3 Jy/Beam km s\(^{-1}\)). Green and blue contours show 98 GHz continuum emission of ALMA Band3 and the integrated intensity of H30\(^+\)α outflow wing detection. The red cross shows the central position of 98 GHz continuum emission. (b) Integrated intensity map of \(^{13}\)CO (J = 2-1). The red contour shows 231 GHz continuum emission of ALMA Band6. The black rectangular area denotes slice paths of the Papillon H II region and the surrounding molecular cloud with three different position angles (see Figure 5).

Table 2

| Object                  | \(n_e\) (cm\(^{-3}\)) | \(M_{\text{ionized}}\) (\(M_\odot\)) | EM (pc cm\(^{-2}\)) | \(U\) (pc cm\(^{-2}\)) | \(N'_c\) (s\(^{-1}\)) | Sp. Type |
|-------------------------|------------------------|----------------------------------------|----------------------|--------------------------|------------------------|----------|
| Papillon Nebula          | 2.2 \times 10^4        | 65                                     | 3.9 \times 10^6      | 153                      | \geq 1.1 \times 10^{30} | \geq O3   |
| YSON159W-N YSO (or YSO-N) | 2.6 \times 10^3        | 154                                    | 6.3 \times 10^6      | 168                      | \geq 1.5 \times 10^{30} | \geq O3   |

comparison to shorter wavelength data and the limitations of the Robitaille et al. (2006) YSO models (Robitaille 2008).

Unlike N159W-N YSO and N159W-S YSO (YSO-N and YSO-S in Fukui et al. 2015), neither the Papillon Nebula YSO nor 054009.49-694453.5 have 12CO(2-1) outflow wing detections. The other two YSOs in N159E identified by Carlson et al. (2012) and indicated with white dots in Figure 1, are less massive without as much 12CO(2-1) or \(^{13}\)CO(2-1) gas detected in their surrounding.

The Papillon Nebula YSO is associated with H30α RRL emission. We determine the electron temperature of the gas (under the assumption of local thermodynamic equilibrium; \(T_e^\alpha\)) using the H30α RRL (Sewilo et al. 2011 and references therein). We use \(T_e^\alpha\) and the observed continuum parameters to determine the electron density (\(n_e\)), ionized gas mass (\(M_{\text{ionized}}\)), emission measure (EM), ionization parameter (\(U\)), and Lyman continuum flux (\(N'_c\)) using equations provided by Mezger & Henderson (1967). The estimated physical properties of the Papillon Nebula YSO are listed in Table 2.

In Table 2, we also include physical parameters estimated for the N159W-N YSO, another high-mass YSO that is associated with the H30α RRL emission in our ALMA observations toward N159 (see Figure 2); its properties can be used for comparison to those of the Papillon Nebula YSO. Both YSOs have similar ionizing properties and are at least O3 stars (Smith et al. 2002). However, the Papillon Nebula YSO has an emission measure that is half of that of the N159W-N YSO. The emission measure is proportional to the optical depth. There is less circumstellar material along the line of sight, i.e., the pole-on orientation as in the case of the Papillon Nebula YSO, compared to N159W-N YSO. The lower emission measure indicates lower optical depth in the Papillon Nebula YSO. Our calculations using H30α RRL and the continuum emission are consistent with the SED fitting results.

Meynadier et al. (2004) use evolutionary track models (Lejeune & Schaerer 2001) to determine that the location of the Papillon Nebula YSO in their color–magnitude diagram best fits a 3 Myr isochrone and the mass of the Papillon Nebula YSO is \(50 M_\odot\). Our results are similar to the previous calculations of mass, photon flux, and spectral type. The differences may be mainly due to uncertainties in extinction, measured fluxes, and theoretical evolutionary tracks. We use mid- to far-IR photometry for SED fitting and the continuum observations to calculate the spectral type; therefore, we are assuming that none of the ionizing photons are escaping. However, this assumption does not always hold. We observe a CO hole around the Papillon Nebula YSO in the present observations (see Figure 4(a) and Section 3.3), but this is not the case for N159W-N YSO. Papillon Nebula YSO is surrounded by the gas of much lower density compared to N159W-N YSO. More photons could be escaping the Papillon Nebula YSO without ionization and our calculations may underestimate the Lyman continuum flux and the stellar mass. This scenario is further supported by Meynadier et al. (2004), who found the Papillon Nebula YSO to not be very embedded (\(A_V \sim 7\) mag) and to be situated on the nearer side of the cloud since it is visible in the optical.

There are nine YSOs in N159 (including the source discussed above; Chen et al. 2010; Carlson et al. 2012; Fukui et al. 2015), one of which is the Herschel-only source (not
detected with Spitzer) and therefore not listed in Table 3. Sources J053943.75-694540.2, J053940.48-694517.3, and J053940.78-694632.0 all have masses less than 15 $M_\odot$. These three YSOs have a dearth of $^{12}$CO(2-1) or $^{13}$CO(2-1) gas near them, similar to the two low-mass YSOs in N159E. Perhaps lower-mass YSOs can form in regions that lack $^{12}$CO(2-1) or $^{13}$CO(2-1); however, they are probably not formed via filamentary collisions. There are three YSOs in N159W and one YSO in N159E that have masses above 30 $M_\odot$: N159W-N YSO, N159W-S YSO, 053937.53-694609.8, and the Papillon Nebula YSO. N159W-N YSO and N159W-S YSO are ~$10^5$ years old and have outflows associated with them (Fukui et al. 2015). Source 053937.53-694609.8 and the Papillon Nebula YSO have a CO hole around them, are both ~$10^5$ years old, and have no outflow wings detected from the CO data. It is plausible to assume that at one point in time both 053937.53-694609.8 and the Papillon Nebula YSO had outflows, and that they are now older and are accreting less material, and have dissipated CO gas around them. Analyses of ALMA $^{12}$CO(2-1) and $^{13}$CO(2-1) gas associated with YSOs in other regions of the LMC will shed more light on differences between higher- and lower-mass star formation and evolution.

3.3. Gas Properties toward the Papillon Nebula

Figure 4(a) shows the Hα image of WFPC2 HST around the Papillon H II blobs (the white rectangular region in Figure 1). The Hα observations revealed the morphology of a “papillon,” a butterfly-shaped ionized nebula with the wings separated by ~2.7′ (0.6 pc) (Heydari-Malayeri et al. 1999). White contours show the velocity-integrated map of $^{12}$CO(2-1). The distribution of molecular gas toward the Papillon Nebula shows a CO hole with a diameter of ~0.6 pc. Blue contours show the RKL, H30α, detected by our ALMA Band 6 observation. The distribution of H30α is tracing the ionized gas, which almost fills the molecular hole. Green contours show the continuum emission at 98 GHz of ALMA Band 3. The 98 GHz continuum emission seems to be dominated by free–free emission from ionized gas since it is several times stronger than the expected thermal dust emission by 231 GHz continuum emission. In this paper, we define the central position of the Papillon Nebula as the central position of 98 GHz continuum emission of ALMA Band 3 (the magenta cross) because it has the highest spatial position accuracy among optically thin emission from ionized gas. Figure 4(b) shows the velocity-integrated intensity image of $^{13}$CO(2-1), showing the distribution of dense gas. The red contour shows the distribution of 231 GHz thermal dust continuum emission observed by ALMA Band 6. The dust emission is located at the edge of the molecular hole. This indicates that the cloud surface is heated by the strong radiation from the high-mass YSO in the Papillon Nebula.

Figure 5 shows the antenna temperature distribution along slices with three different position angles around the Papillon H II region (see the dashed box in Figure 4(b)). Offset center is set to the central position of Papillon Nebula. Red solid and dashed lines show 200 times the antenna temperature of 98 and 231 GHz continuum emission. Black and blue lines show the peak antenna temperature distribution of $^{12}$CO(2-1) and $^{13}$CO(2-1).

Table 3

| Source Name | Other Name | $M_{\text{dyn}}$ ($M_\odot$) | $L_{\text{bol}}$ ($L_\odot$) | Evol. Stage | Reference |
|-------------|------------|-----------------------------|-----------------------------|-------------|-----------|
| 053937.56-694525.4 | N159W-N YSO (or YSO-N) | $34.8 \pm 8.4$ | $(2.7 \pm 1.5) \times 10^5$ | I | 1 |
| J053941.89-694612.0 | N159W-S YSO (or YSO-S) | $33.7 \pm 2.6$ | $(1.7 \pm 0.3) \times 10^5$ | I | 1 |
| J053943.75-694540.2 | ... | $9.4 \pm 3.1$ | $(5.1 \pm 13) \times 10^3$ | I | 1 |
| J053940.78-694517.3 | ... | $11.6 \pm 1.0$ | $(4.2 \pm 0.1) \times 10^3$ | I | 2 |
| J053940.78-694632.0 | ... | $9.4 \pm 2.7$ | $(5.7 \pm 2.8) \times 10^3$ | I | 2 |
| J053939.59-694604.1 | ... | $18.5 \pm 1.4$ | $(4.5 \pm 0.0) \times 10^4$ | I | 1 |
| J053937.53-694609.8 | ... | $31.2 \pm 2.9$ | $(2.2 \pm 0.4) \times 10^5$ | I | 1 |
| J053937.04-694536.7 | ... | $28.4 \pm 0.8$ | $(1.1 \pm 0.4) \times 10^5$ | I | 2 |

Note.

* Same as in Table 1.

References. (1) Chen et al. (2010), (2) Carlson et al. (2012).
gas is heated by the UV from the Papillon Nebula YSO. Molecular line intensity is steeply dropped toward the Papillon and forms a molecular hole. The molecular hole is filled by 98 GHz continuum emission (red solid lines). Except for direction of P.A. = +23°, 231 GHz thermal dust emission (red dashed lines) has a peak at the surface of molecular cloud. This is in contrast with the situation toward two YSOs, N159W-N YSO and N159W-S YSO, in N159W, which are located at the peak of the CO clouds. This fact is also consistent with the idea that the Papillon Nebula is in a later evolutionary stage than the N159W YSOs. The lack of the outflowing gas also supports the evolved nature of the source, indicating that the mass accretion onto the YSO in the Papillon Nebula has halted.

We do not see significant absorption in the Hα emission image toward the region where the CO is detected. The column density of the molecular gas toward the Hα emission is as high as $2 \times 10^{23}$ cm$^{-2}$, implying that the Papillon is located in front of the molecular clouds facing us. This fact is consistent with the discussion by Meynadier et al. (2004), as shown in Section 3.2.

The high antenna temperature of $^{12}$CO(2-1) toward the interface region could be explained by the fact that the heated surface of the molecular cloud is on the near side. The mass of the ionized dense gas is estimated to be $65 \, M_\odot$ from the H$^\alpha$ observations (Table 2). The total flux of 231 GHz continuum emission around Papillon Nebula within the radius of 1pc is $\sim 90$ mJy. The mass of the dust cloud is then calculated to be $5340 \, (\frac{\sigma}{3.5 \times 10^{-3}}) \, M_\odot$ by assuming that the continuum is only from the dust thermal emission. Here, we assumed the absorption coefficient per unit dust mass at 1.2 mm and the dust-to-gas mass ratio is $0.77 \, cm^{2} g^{-1}$ and $3.5 \times 10^{-3}$, respectively (Herrera et al. 2013; Fukui et al. 2015). Figure 4(b) shows that about half of the dust emission comes from the CO hole, indicating that the gas mass without CO emission is as large as a few thousand $M_\odot$ inside the CO hole.

3.4. Filaments toward the Papillon Nebula

Previous observations of molecular clouds in high-mass star-forming regions showed that multiple velocity components were often observed toward high-mass YSOs/clusters, and this fact is considered to be a possible consequence of the past cloud–cloud collisions (Furukawa et al. 2009; Ohama et al. 2010; Torii et al. 2011, 2015; Fukui et al. 2015, 2016). Also in the case of N159E, the complex velocity structure is seen toward the molecular cloud associated with the Papillon. We then focus on this region in order to investigate the origin of the high-mass YSOs.

Figures 6(a) and 5(b) show kinematic structures of the associated clouds with Papillon Nebula. Although the velocity-integrated intensity image in Figure 4(b) shows that the cloud associated with the Papillon Nebula looks like a single clump, the velocity structure suggests that it consists of a different velocity component. The velocity distribution in $^{12}$CO(2-1) shown in Figure 6(a) indicates that the velocity of the molecular gas varies by $\sim 10$ km s$^{-1}$ in the cloud complex. The velocity channel maps in Figure 3 indicate that the complex can be divided into a few filaments with different velocities. Figure 6(b) shows the three velocity components; blue ($-8.0$ km s$^{-1}$ to $-1.6$ km s$^{-1}$), green ($-1.4$ km s$^{-1}$ to $+1.0$ km s$^{-1}$), and red ($+1.2$ km s$^{-1}$ to $+7.8$ km s$^{-1}$). Each velocity component has filamentary structures, and they apparently merge around the region where the hole is located. This morphology and the size scale are similar to the N159W-S filament that shows high-mass star formation induced by two filaments collision (see Figure 6(c)); though, the situation is more complex than in the N159E filaments.

Figure 7 shows the PV diagrams along each filament. The slice regions of the PV diagrams are shown as dashed magenta rectangles in Figure 6(b). Velocity is the relative velocity against the system velocity of N159E and the position denotes the offset positions from the center of Papillon Nebula (magenta cross symbol in Figure 6(b)). Each filament clearly has two regions with different line widths. The line width measured as the Full Width at Half Maximum of each filament is 4–6 km s$^{-1}$ in a place near the Papillon and is 2–3 km s$^{-1}$ in a place far from the Papillon. Within the $3''$ ($\sim 0.75$ pc) from the Papillon, the centroid velocity of all filamentary clouds are merged into the velocity of blue filament (approximately $-2$ km s$^{-1}$).
4. DISCUSSION: FILAMENTARY COLLISION AS A MECHANISM OF FORMATION OF HIGH-MASS STARS

The present work has shown that the molecular gas in the N159E region is remarkably filamentary. The typical width and projection length of the filaments are $\sim 1$ pc and 5–10 pc, and the filamentary nature is similar to the N159W region (Fukui et al. 2015), suggesting that the filamentary distribution is common in GMCs. The most outstanding young star in N159E is the Papillon Nebula. We shall hereafter focus on Papillon and discuss star-formation properties, which are characteristic to the filamentary cloud distribution in N159. Papillon is located toward an intersection of the three filaments, as shown in Figures 6(a) and (b). We find three major differences between Papillon and N159W-S: (1) the Papillon Nebula YSO is associated with the compact H II region, whereas the N159W-S YSO has no detectable H II region, (2) the N159W-S YSO is associated with very young protostellar outflow, though the Papillon YSO has no outflow, and (3) the Papillon Nebula YSO is associated with the third filament that is nearly orthogonal to the other two filaments, while N159W-S YSO is associated with two filaments. The stellar masses of the N159W-S YSO and Papillon Nebula YSO are $\sim 40 M_\odot$ and $\sim 30 M_\odot$, respectively, and both of them are O stars capable of forming an H II region. These facts are consistent with the idea that the Papillon is in an evolutionary stage later than N159W-S, when outflow is halted and an H II region is developed. Fukui et al. (2015) suggested that the V-shaped filaments collided with each other to trigger the O star formation in N159W-S. It is natural that a similar filamentary collision, possibly a triple collision, took place in Papillon. In particular, the two filaments, Green and Red, show remarkably similar velocity distributions to the two filaments in N159W-S, where the intersection between the two filaments remains unionized (Figure 3 of Fukui et al. 2015). The molecular filaments in Papillon are not extended toward the O star due to the ionization. The third Blue filament may be colliding also with the other two. The collisional interaction is consistent with the line broadening near the Papillon Nebula in the PV diagrams in Figure 7 as discussed in case of N159W-S; cloud–cloud collision excites isotropic turbulence for which the velocity span is similar to the true relative velocity (Inoue & Fukui 2013). The velocity span in the broadened region is as large as $9 \text{ km s}^{-1}$, suggesting the relative velocity of the collision is about $9 \text{ km s}^{-1}$. We see signs of the line broadening even at an offset about 11 and 7 arcsec from the O star in Red and Green where the H II region is not extended (Figure 7). The broadening, thus, seems not to be due to the dynamical effect of the H II region. We in addition note that the Red filament is associated with weak emission filling the area between the Red and Green filaments. Similar weak emission is also seen in case of N159W-S (Figure 6). We suggest that these weak emissions may represent the low-density envelopes of the filaments, which are heated-up mildly by the collisional shock interaction. The above scenario suggests that the timescale of the collision is estimated to be 2 pc divided by $9 \text{ km s}^{-1}$, i.e., $2 \times 10^5$ year, which is similar to the timescales of the collision and the stellar age of Papillon Nebula YSO. We suggest that the formation of the O star, i.e., mass accretion onto the protostellar core, was initiated just after the filamentary collision. The O star associated with the Papillon Nebula is more evolved than N159W-S for which the outflow has a dynamical timescale of

![Figure 7. Position–velocity diagrams of blue, green, and red filaments of N159E (magenta rectangles in Figure 6(b)). Widths of the region of blue, green, and red filaments are 0.7 pc, 0.7 pc, and 1.4 pc, respectively. The offset positions of Papillon (magenta cross in Figure 5(b)) show magenta horizontal lines (offset = 0 arcsec).](image)

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For a stellar mass of $30 M_\odot$ and the timescale of $2 \times 10^5$ years, the mass-accretion rate is estimated to be $\sim 10^{-4} M_\odot$ yr$^{-1}$. This mass-accretion rate satisfies the requirement to overcome the radiation pressure (Wolfire & Cassinelli 1987).

The small velocity difference between the two filaments suggests that the relative motion makes an angle to the line of sight rather close to $90^\circ$ as in case of N159W-S. This in turn indicates that the angle between the two filaments can be significantly affected by the projection and may be much larger than the projected one, $\sim 20^\circ$. The similar filamentary collision both in N159W and N159E suggests that such a collision may be frequent in N159 and in the LMC, being possibly a major mode of O star formation. If we tentatively assume a collision between two filaments of 10 pc length, which move in a direction vertical to their elongation at a relative velocity of $10 \text{ km s}^{-1}$ with an angle of $90^\circ$ projected on a plane normal to the relative motion, the volume where filamentary collision takes place can be large (10 pc)$^3$ in 1 Myr for a GMC size of 20 pc, in the order of 10% of the total volume of the GMC (20 pc)$^3$. Given the typical evolutionary timescale of a GMC $10 \text{ Myr}$ (Fukui & Kawamura 2010), such a collision should happen fairly frequently as is consistent with the observations. It is intriguing that Papillon and N159W-S show similar morphology of the colliding V-shaped filaments (Figure 6) in spite of the separation of 100 pc in projection. We suggest that the whole N159 region including N159W and N159E may be subject to large-scale acceleration or compression driven over a few $100 \text{ pc-scale}$ supershell(s). We speculate that such a compression may help to organize the magnetic field in a common direction both in N159W and N159E.

5. CONCLUSIONS

We observed the N159E GMC in the LMC with the ALMA Band 3 and Band 6. In this paper, we showed the results of $^{12}\text{CO}$(2-1), $^{13}\text{CO}$(2-1), H3$\alpha$ hydrogen recombination line, free–free emission around 98 GHz, and dust thermal emission around 230 GHz. Conclusions of the present work are given as follows.

1. The prominent feature of the molecular gas distribution in N159E is three belt-like structures extending from the northeast to the southwest with lengths of 10–20 pc (see Figure 1). It is coincident with the dark lane in the optical H$\alpha$ images (see Figure 2). The total molecular mass of N159E in the present map is calculated to be $0.92 \times 10^4 M_\odot$ from the $^{13}\text{CO}$(2-1) intensity.

2. N159E is the complex of filamentary clouds with a width of $\sim 1 \text{ pc}$ scale and projection length of a several parsec scale (see Figure 3). Typical molecular mass and velocity dispersion of the filamentary clouds are a few thousand $M_\odot$ and $\sim 1 \text{ km s}^{-1}$.

3. We found a molecular hole with a radius of $\sim 0.5 \text{ pc}$ around the $\sim 40 M_\odot$ massive YSO in N159E (so-called the Papillon Nebula YSO). This molecular hole is filled by 98 GHz free–free emission and H3$\alpha$ hydrogen recombination emission temperature. Temperature of molecular gas around the hole is as high as $\sim 80 \text{ K}$. This massive YSO has enough luminosity to ionize the filamentary clouds within a life time. It indicates that the Papillon Nebula YSO has just moved to the initial phase of dispersal of the parental molecular cloud from the protostellar phase.

4. The Papillon Nebula YSO is clearly located at the overlapping point of three filamentary clouds of different velocities. This kinematic structure suggests that the formation of the massive protostar was induced by the collision of filamentary clouds. Similar kinematic structure was reported by Fukui et al. (2015) in N159W-N and N159W-S. These three objects are the massive YSO candidates that have masses of $\geq 35 M_\odot$ associated with strong molecular emission in N159E and N159W region. This fact suggests strongly that such a collision of filamentary clouds is a primary or important mechanism of very-high-mass star formation.

5. The collision of filamentary clouds is expected to occur frequently during the GMC evolutionary timescale of $10 \text{ Myr}$ if we assume a relative speed of $10 \text{ km s}^{-1}$ and a length of 10 pc. It suggests that high-mass star formation induced by collision of filamentary cloud occur generally during the life of the molecular cloud.

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