Formation of the Active Star-forming Region LHA 120-N 44 Triggered by Tidally Driven Colliding H I Flows

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Abstract

The second most active site of high-mass star formation next to R136 in the Large Magellanic Cloud (LMC) is N44. We carried out a detailed analysis of H I at 60″ resolution by using the ATCA and Parkes data. We presented decomposition of the H I emission into two velocity components (the L and D components) with a velocity separation of ~60 km s^{-1}. In addition, we newly defined the I component whose velocity is intermediate between the L and D components. The D component was used to derive the rotation curve of the LMC disk, which is consistent with the stellar rotation curve. Toward the active cluster-forming region of LHA 120-N 44, the three velocity components of H I gas show signatures of dynamical interaction, including bridges and complementary spatial distributions. We hypothesize that the L and D components have been colliding with each other since ~5 Myr ago, and the interaction triggered formation of the O and early-B stars ionizing N44. In the hypothesis, the I component is interpreted as decelerated gas in terms of momentum exchange in the collisional interaction of the L and D components. In the N44 region, the Planck submillimeter dust optical depth is correlated with the H I column density, which is well approximated by a linear regression. We found that the N44 region shows a significantly steeper regression line than in the bar region, indicating less dust abundance in the N44 region, which is ascribed to the tidal interaction between the LMC and the SMC 0.2 Gyr ago.

Key words: galaxies: ISM – galaxies: star formation – H II regions – ISM: atoms – (galaxies:) Magellanic Clouds – stars: massive

1. Introduction

1.1. High-mass Star Formation

The formation mechanism of high-mass stars is one of the most important issues in astronomy, because their extremely energetic interactions with surrounding material in the form of ultraviolet (UV) radiation, stellar winds, and supernova explosions are influential in driving galaxy evolution. Two models, the competitive accretion and the monolithic collapse, have been major theoretical schemes of high-mass star formation (for reviews, see Zinnecker & Yorke 2007; Tan et al. 2014). In spite of the numerous studies, we have not understood the detailed mechanisms of high-mass star formation.

Recently, the cloud–cloud collision (CCC) model (Habe & Ohta 1992; Anathpindika 2010) attracted attention as a mechanism of high-mass star formation, and observational studies showed that more than 30 regions of high-mass stars and/or clusters are triggered by CCC: NGC 1333 (Loren 1976), Sgr B2 (Hasegawa et al. 1994; Sato et al. 2000), Westerlund 2 (Furukawa et al. 2009; Ohama et al. 2010), NGC 3603 (Fukui et al. 2014a), RCW 38 (Fukui et al. 2016), M42 (Fukui et al. 2018d), NGC 6334/NGC 6357 (Fukui et al. 2018a), M17 (Nishimura et al. 2018), W49 A (Miyawaki et al. 1986, 2009), W51 (Okumura et al. 2001; Fujita et al. 2017), W33 (Kohno et al. 2018b), M20 (Tori et al. 2011, 2017a), RCW 120 (Tori et al. 2015), [CPA2006] N37 (Baug et al. 2016), GM 24 (Fukui et al. 2018b), M16 (Nishimura et al. 2017), RCW 34 (Hayashi et al. 2018), RCW 36 (Sano et al. 2018), RCW 32 (Enokiya et al. 2018), RCW 166 (Ohama et al. 2018a), Sh2-48 (Tori et al. 2017c), Sh2-252 (Shimoikura et al. 2013), Sh2-235, 237, 53 (Dewangan et al. 2016, 2017b, 2018b), LDN 1004E in the Cygnus OB 7 (Dobashi et al. 2014), [CPA2006] S36 (Tori et al. 2017b), [CPA2006] N35 (Tori et al. 2018), [CPA2006] N4 (Fujita et al. 2018), [CPA2006] S44 (Kohno et al. 2018a), [CPA2006] N36 (Dewangan et al. 2018a), [CPA2006] N49 (Dewangan et al. 2017a), LHA 120-N159 West (Fukui et al. 2015a), [CPA2006] S116 (Fukui et al. 2018c), LDN 1188 (Gong et al. 2017), LDN 1641-N (Nakamura et al. 2012), Serpens South (Nakamura et al. 2014), NGC 2024 (Ohama et al. 2017), RCW 79 (Ohama et al. 2018b), LHA 120-N159 East (Saito et al. 2017), NGC 2359 (Sano et al. 2017), Circinus-E cloud (Shimoikura & Dobashi 2011), G337.916, G337.916E (Tori et al. 2017b), Rosette Molecular Cloud (Li et al. 2018), Galactic center (Tsui & Oka 2015), G35.2N and G35.2S (Dewangan et al. 2017), NGC 2068/NGC 2071 (Tsuchiura et al. 2017), and NGC 604 (Tachihara et al. 2018). These studies lend support for the role of CCC, which triggers formation of O stars. A typical collision size scale and relative velocity between the two clouds are 1–10 pc and 10–20 km s^{-1}, and the number of O-type stars formed by the collision is in a range from 1 to ~20 for H2 column density greater than ~10^{22} cm^{-2}. The CCC model realizes gas compression by two orders of magnitude within 10^5 yr (~1 pc/10 km s^{-1}) and provides a high mass accretion rate by supersonic collision between molecular clouds. These phenomena clearly create physical conditions that favor high-mass star formation according to theoretical simulations of the collisional process in the realistic inhomogeneous molecular gas (Inoue & Fukui 2013; Inoue et al. 2018), whereas it remains to be observationally established how unique and common the role of the collisions is in the O-type star.
formation. In this context, we note that a large-scale model of molecular cloud evolution via collision demonstrates the important role of collision in star formation and cloud growth (Kobayashi et al. 2018).

One of the observational signatures of CCCs is complementary distribution between the two colliding clouds. It is usual that the colliding two clouds have different sizes as simulated by theoretical studies (Habe & Ohta 1992; Ananthpindika 2010; Takahira et al. 2014). If one of the colliding clouds is smaller than the other, the small cloud creates a cavity of its size in the large cloud through the collision. The cavity is observed as an intensity depression in the gas distribution at a velocity range of the large cloud, and the distributions of the small cloud and the cavity exhibit a complementary spatial distribution. The complementary distributions often have some displacement because the relative motion of the collision generally makes a nonnegligible angle to the line of sight. Fukui et al. (2018d) presented synthetic observations by using the hydrodynamical numerical simulations of Takahira et al. (2014). In previous works, there are more than six regions where the displacement was well determined, including M17 (Nishimura et al. 2018), M42 (Fukui et al. 2018d), RCW 36 (Sano et al. 2018), GM 24 (Fukui et al. 2018b), S116 (Fukui et al. 2018c), and R136 (Paper I).

The collisional process on a few–10 pc scale was investigated by magnetohydrodynamic (MHD) numerical simulations. These simulations show that the HI gas flow colliding at 20 km s\(^{-1}\) is able to compress HI gas, and the density of HI gas is enhanced in the compressed layer (Inoue & Inutsuka 2012). Molecular clouds are formed in the shock-compressed layer in a timescale of \(\sim 10\) Myr, which can probably become shorter to a few Myr when the colliding velocity is as fast as 100 km s\(^{-1}\) if the density is higher. These clouds will become self-gravitating when they grow massive enough. Inoue & Fukui (2013) and Inoue et al. (2018) calculated the subsequent physical process where two molecular gas flows collide at 20 km s\(^{-1}\). These studies show that strong shock waves are generated by a CCC from gravitationally unstable massive molecular cores, each of which directly leads to forming a high-mass star.

1.2. Previous Study of the LMC

In the context of CCC, the nearest galaxies to our Galaxy, the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC) (Fukui & Kawamura et al. 2010), provide an excellent laboratory to test star formation and collisional triggering. Luks & Rohlfis (1992) separated two HI velocity components of the LMC whose velocity difference is \(\sim 50\) km s\(^{-1}\); one is the HI gas extending over the whole disk of the LMC (hereafter the D component), and the other is the more spatially confined HI having lower radial velocity (hereafter the L component). They analyzed the HI data obtained by the Parkes telescope with angular resolution and grid size of 15′ and 12′, respectively, and they found that the D and L components contain 72% and 19% of the whole HI gas, respectively. In spite of the work by Luks & Rohlfis (1992), the implications of the two components for star formation were not observationally explored for nearly two decades.

Recently, it was found that the young massive cluster RMC136 (R136) in the LMC is located toward an overlapping area of the L and D components (Fukui et al. 2017a, hereafter Paper I). These authors analyzed the HI data of the whole LMC at 1′ resolution, which corresponds to 15 pc at the distance of the LMC (Kim et al. 2003), and separated the L and D components at a higher resolution. Figure 1 shows a typical HI spectrum that presents the L and D components. The authors of (Paper I), revealed that the two components are linked by the bridge features in the velocity space and show complementary spatial distributions on a kpc scale. Based on these two signatures, it was suggested that the L and D components are colliding toward R136, and a scenario was presented that the collision of the HI flows triggered the formation of the R136 cluster and high-mass stars in its surroundings. They also showed that there is a component having intermediate velocity between the L and D components (hereafter the I component) and indicated that the I component may represent the merging of the L and D components where their relative velocity is decelerated with momentum conservation (see Figure 2 of Paper I). According to the theoretical studies including hydrodynamical numerical simulations, the LMC and SMC had a close encounter 0.2 Gyr ago, and their tidal interaction stripped gas from the two galaxies. Currently, the remnant gas is falling down to each galaxy and observed as the HI gas with significant relative velocity (Fujimoto & Noguchi 1990; Bekki & Chiba 2007a; Yozin & Bekki 2014).

1.3. LHA 120-N 44

We extend the study from R136 to other active HI regions in the LMC to test how the colliding gas flow leads to massive star formation. Following Paper I, we analyze the region of LHA 120-N 44 (N44) in the present paper. The HI region cataloged by Henize (1956), N44 is one of the most active star-forming regions in the LMC. It is older (5–6 Myr; Will et al. 1997) than R136 (1.5–4.7 Myr; Schneider et al. 2018). It holds the second-largest number of O/WR stars, \(\sim 40\), corresponding to \(\sim 1/10\) of R136 (Bonanos et al. 2009) in the LMC, and N44 has received much attention at various wavelengths from millimeter/submillimeter, infrared, optical, and high-energy X-rays (e.g., Oey & Massey 1995; Kim et al. 1998a; Chen et al. 2009; Carlson et al. 2012). This region is also categorized as a superbubble by an H\(_\alpha\) shell, and the OB association LH 47 is located in the center of the shell. Ambrocio-Cruz et al. (2016) investigated the kinematic features of H\(_\alpha\) emission and compared it with the L and D components. These authors showed that compact HI regions N44 B and C have two H\(_\alpha\) components with a velocity difference of \(\sim 30\) km s\(^{-1}\) and interpreted that N44 B and C belong to the L and D components, respectively. Kim et al. (1998a) analyzed the high-resolution HI data toward N44 and indicated that the HI shell corresponding to the H\(_\alpha\) shell was produced by stellar winds and supernovae, whereas the relationship between the shells and the L and D components remains unknown. These previous studies show that the N44 region is the most suitable target for studying high-mass star formation next to R136.

The present paper is organized as follows. Section 2 summarizes the data sets and methodology, and Section 3 gives the results. The discussion is given in Section 4, in which we test whether the high-mass star formation in N44 has been triggered by the colliding HI flows. Section 5 gives a summary.
2. Data Set and Masking

2.1. Data Sets

2.1.1. H I

Archival data of the Australia Telescope Compact Array (ATCA) and Parkes H I 21 cm line emission are used (Kim et al. 2003). The angular resolution of the combined H I data is 60″ (∼15 pc at the LMC). The rms noise level of the data is ∼2.4 K for a velocity resolution of 1.649 km s$^{-1}$. They combined the H I data obtained by ATCA (Kim et al. 1998b) with those obtained with the Parkes multibeam receiver with a resolution of 14′–16′ (Staveley-Smith 1997). This is because the ATCA is not sensitive to structures extending over 10′–20′ (∼150–160 pc) due to the minimum baseline of 30 m.

2.1.2. Planck/IRAS

Archival data sets of the dust optical depth at 353 GHz ($\tau_{353}$) and dust temperature ($T_d$) were obtained by using the combined Planck/IRAS data with the graybody fitting. For details, see Planck Collaboration et al. (2014). These data sets are used to make comparisons with the H I data. The angular resolution is 5′0 (∼75 pc at the LMC) with a grid spacing of 2′/4. For a comparison of $\tau_{353}$ with H I, the spatial resolution and grid size of H I were adjusted to $\tau_{353}$.

2.1.3. CO

We used $^{12}$CO($J = 1$–$0$) data of the Magellanic Mopra Assessment (MAGMA; Wong et al. 2011) for a small-scale analysis in the N44 region. The effective spatial resolution is 45″ (11 pc at a distance of 50 kpc), and the velocity resolution is $0.526$ km s$^{-1}$. The MAGMA survey does not cover the whole LMC, and the observed area is limited toward the individual CO clouds detected by NANTEN (Fukui et al. 1999; Mizuno et al. 2001).

We used the data of $^{12}$CO($J = 1$–$0$) observed over the whole LMC with the NANTEN 4 m telescope at a resolution of 2′/6, grid spacing of 2′/0, and velocity resolution of 0.65 km s$^{-1}$ (Fukui et al. 1999, 2008; Kawamura et al. 2009). In the present paper, the NANTEN data were used to mask the CO-emitting regions in comparing the Planck/IRAS data with the H I.

2.1.4. Hα

The Hα data of the Magellanic Cloud Emission-Line Survey (MCELS; Smith & MCELS Team 1999) are used for a comparison of spatial distribution with H I. The data set was obtained with a 2048 × 2048 CCD camera on the Curtis Schmidt Telescope at Cerro Tololo Inter-American Observatory. The angular resolution is ∼3″–4″ (∼0.75–1.0 pc at a distance of 50 kpc). We also use the archival data of Hα provided by the Southern H-Alpha Sky Survey Atlas (SHASSA; Gaustad et al. 2001) in order to define the region where UV radiation is locally enhanced. The same method was also applied in Paper I; hence, we can compare the result of R136 with that of N44. The angular resolution is about 0′/8, and the sensitivity level is $2 \text{R} (1.2 \times 10^{-17} \text{erg cm}^{-2} \text{s}^{-1} \text{arcsec}^{-2})$ pixel$^{-1}$.

2.2. Masking

We masked some regions in the distribution of the dust optical depth at 353 GHz ($\tau_{353}$) in order to avoid the effect of local dust destruction by the UV radiation from O-type stars/H II regions in comparison to $\tau_{353}$ with H I. Such a local effect may alter the dust properties, which are assumed to be uniform in the comparison, and can distort the correlation between H I and dust emission. By using CO and Hα data, the regions with CO emission higher than $1 \text{K km s}^{-1}$ (∼1σ) with Hα emission higher than 30 R are masked, as in the previous works (Fukui et al. 2014b, 2015b; Okamoto et al. 2017).
3. Results

3.1. Method of H I Spectral Decomposition

In Paper I, H I gas decomposition into the L and D components was demonstrated, but details were not given. We therefore describe a method of the decomposition used in the present paper and in Paper I as Appendix A. In order to decompose the H I spectra into the L and D components, we made Gaussian fittings to the H I data. We fitted the Gaussian function to the H I emission lines for each pixel with peak intensity greater than 20 K and derived the peak velocity of the spectrum. This process allowed us to derive the velocity of the D component toward the areas where the L component is weaker than the D component. For the profiles showing the L component as the primary peak, we made another fitting to the secondary peak and defined the D component if the secondary peak velocity was larger than the primary peak. We thus obtained the distribution of the D component over the disk. The result was used to derive the rotation velocity of the disk. Then, we subtracted the rotation velocity for each pixel by shifting the spectra in the velocity channel over the LMC. We defined the \( V_{\text{offset}} \) as the relative velocity to the D component as follows: \( V_{\text{offset}} = V_{\text{LSR}} - V_D \) (\( V_D \) = the radial velocity of the D component). Hereafter, we use \( V_{\text{offset}} \) instead of \( V_{\text{LSR}} \) in the following.

We determined the typical velocity ranges of the L and D components as \( V_{\text{offset}} \) from -100 to -30 km s\(^{-1}\) and from -10 to +10 km s\(^{-1}\), respectively, over the whole galaxy from position–velocity diagrams and the velocity channel map in Paper I. We also defined the intermediate velocity between the L and D components in a range of \( V_{\text{offset}} \) from -30 to -10 km s\(^{-1}\) (I component). The maximum variation of the velocity range is about \( \pm 10 \) km s\(^{-1}\).

We note that these velocity ranges vary from region to region, which requires fine-tuning in the individual regions due to the velocity variation of the L component.

3.2. The Rotation Curve of the LMC

We derived the rotation curve of the LMC represented by the velocity distribution of the D component as shown in Figure 2(c). As described in Appendix B, we optimized the coordinate of the rotation center, the inclination angle of the galaxy disk plane, and the position angle of the inclination axis. The present curve shows that the flat rotation of the LMC with a constant rotation velocity of \( \sim 60 \) km s\(^{-1}\) at the galactocentric radius \( R_G \) is larger than 1 kpc and consistent with the stellar disk rotation as shown in Figure 2(c). The previous rotation velocity of H I (Kim et al. 1998b) decreases at \( R_G > 2.5 \) kpc. Kim et al. (1998b) did not consider the two velocity components, and their rotation velocity is from a mixture of the L and D components. Moreover, it is likely that the extended emission was resolved out, since they used the H I data taken with the ATCA alone. In the present study, we use the combined ATCA and Parkes H I data, and the missing flux is recovered.

3.3. Distribution of the L and D components

We compare the H I distribution with the major star-forming regions over the whole LMC. Figures 3(a) and (b) present distributions of the L and D components, and Figure 3(c) is an overlay of the two components. The L-component distribution is concentrated in two regions. One of them is the H I ridge stretching \( \sim 1 \) kpc \( \times 2.5 \) kpc in R.A. and decl., including young star-forming regions R136 and LHA 120-N159. The other region is extended to the northwest from the center of the LMC with a size of \( \sim 2 \) kpc \( \times 2 \) kpc, including N44 (hereafter the diffuse L component). The mean intensity of the diffuse L component is \( \sim 40 \% \) of that of the H I ridge. Several H I regions (Ambrocio-Cruz et al. 2016) are located in the south of the diffuse L component. The D component is extended over the entire LMC and characterized by the morphological properties with many cavities and voids (e.g., Kim et al. 1998b; Dawson et al. 2013).

3.4. Velocity Distribution of the H I Gas toward the N44 Region

Figure 4(a) shows H I total intensity distribution toward the presently analyzed region of N44. The H I gas is concentrated in the region within \( \sim 200 \) pc of N44 C, and its H I integrated intensity is enhanced to 2000 K km s\(^{-1}\). Figure 4(b) is an H\( \alpha \) image (MCELS; Smith & MCELS Team 1999) of the star-forming region indicated by a black box in Figure 4(a). Regions N44 B and N44 C are located in a shell (white dashed circle) whose central coordinate is (R.A., decl.) \( \sim (5^h22^m15^s, -67^d57^m00^s) \). The shell includes a WR star and 35 O-type stars. In the southeast, there is another H I region, N44 D, containing two O-type stars (Bonanos et al. 2009).

Figure 5 shows typical spectra of H I in the northeast and south of N44. There are two velocity components with \( V_{\text{offset}} \) of \( \sim -60 \) and \( \sim -30 \) km s\(^{-1}\), besides the D component. In Figure 5(a), we find that the L component is peaked at \( -60 \) km s\(^{-1}\) and \( 10 \) km s\(^{-1}\) higher than that shown in Figure 1, while the D component is peaked at 0 km s\(^{-1}\). The L and D components are connected by a bridge feature between the two velocity components. We interpret the component at \( V_{\text{offset}} = -80.6 \) to \( -50.0 \) km s\(^{-1}\) as part of the L component and that at \( V_{\text{offset}} = -50.0 \) to \( -15.6 \) km s\(^{-1}\) as part of the I component. In Figure 5(b), no L component is seen, and we interpret that there is only the I component at \( V_{\text{offset}} = -50.0 \) to \( -15.6 \) km s\(^{-1}\). In comparing the H I with the O-type stars, we focus on lines A, B, and C in Figure 4(a), where most of the massive stars in N44 are concentrated.

Figure 6 shows decl.–velocity diagrams integrated in the R.A. direction along lines A, B, and C, which have a width of \( \sim 87 \) pc and a length of \( \sim 1.1 \) kpc in Figure 4(a). Lines A, B, and C pass the eastern, central, and western regions of N44, respectively. In line A (Figure 6(a)), the D and L components are located at decl. \( = -67^d45^m00^s \) to \( -68^d40^m00^s \) and \( -67^d50^m00^s \) to \( -68^d00^m00^s \), respectively. The bridge feature connects them at the position shown by a white dashed box in velocity space. In line B (Figure 6(b)), the D and I components are seen at decl. \( = -67^d30^m00^s \) to \( -68^d09^m00^s \) and \( -68^d03^m00^s \) to \( -68^d15^m00^s \), respectively. A bridge feature shown by a white dashed box connects them. The D, I, and L components are distributed in line C (Figure 6(c)). We also see bridge features like in the other lines, as indicated by white dashed boxes. At the position of decl. \( = -68^d06^m00^s \) to \( -68^d15^m00^s \), the L and D components are connected by another bridge feature, and at decl. \( = -68^d30^m00^s \) to \( -68^d40^m00^s \), the I and D components are connected by a bridge feature.

3.5. The Spatial Distribution of H I Gas toward the N44 Region

Detailed spatial distributions of the L, I, and D components around N44 are shown in Figure 7. The L component is
distributed in the northeastern and southwestern regions of N44 (Figure 7(a)). The I component is extended by ~200 pc × 400 pc in the south of N44 (Figure 7(b)). The D component mainly spreads from the central region to southeast of N44 (Figure 7(c)).

Comparisons of spatial distributions of different velocity components are shown in Figure 8, which shows the distribution of the D component (~15.6 to +9.7 km s⁻¹) overlaid on the L-component contours. The L component has complementary distributions with the D component at the positions of (R.A., decl.) = (5°22'30"–5°24'00", −67°50'00" to −68°40'00") and (5°20'00"–5°22'30", −68°20'00" to −68°40'00"), as indicated by black arrows. Two of the L components exist along the edge of the D component. We interpret that the two depressions in the D component, which correspond to the L components, may represent interaction between the two components. There are more intensity depressions where no corresponding L components are seen. They are possibly due to preexisting intensity variations or created by other mechanisms, like supernovae.

In Figure 9, the D component shows intensity depression toward the I component at the position of (R.A., decl.) ~ (−67°58'00" to −68°26'00", 5°18'00"–5°22'00"), as indicated by the red box. We find some displacement of the complementary distribution between the I and D components, which is a usual signature caused by a certain angle of CCC to the line of sight (Fukui et al. 2018d). We calculated the displacement by using the overlapping function $H(\Delta)$ in pc², which shows a...
degree of complementarity (Fukui et al. 2018d). We derived the projected displacement where the overlapping area of the strong I component (intensity larger than 550 K km s\(^{-1}\)) and the depression of the D component (intensity smaller than 1100 K km s\(^{-1}\)) become maximum.

In Figure 9(b), the I component is surrounded by the D component at (R.A., decl.) = (−68\(^{d}\)4\(^{m}\)0\(^{s}\) to −68\(^{d}\)42\(^{m}\)00\(^{s}\), 5\(^{h}\)18\(^{m}\)00\(^{s}\) to 5\(^{h}\)26\(^{m}\)00\(^{s}\)), as indicated by the black box. They present complementary distributions with a displacement of 107 pc and a position angle of 180\(^{\circ}\).

Figure 10 shows an enlarged view of the N44 region showing complementary distributions among the D, I, and L components on an ~100 pc scale. The D and I components have complementary distribution at (R.A., decl.) ∼ (5\(^{h}\)21\(^{m}\)30\(^{s}\)−5\(^{h}\)24\(^{m}\)00\(^{s}\), −68\(^{d}\)5\(^{m}\)00\(^{s}\) to −68\(^{d}\)10\(^{m}\)00\(^{s}\)), and the L and D components show complementary distribution at (R.A., decl.) ∼ (5\(^{h}\)23\(^{m}\)00\(^{s}\)−5\(^{h}\)23\(^{m}\)36\(^{s}\), −67\(^{d}\)58\(^{m}\)00\(^{s}\) to −67\(^{d}\)52\(^{m}\)00\(^{s}\)) and (5\(^{h}\)20\(^{m}\)30\(^{s}\)−5\(^{h}\)21\(^{m}\)30\(^{s}\), −68\(^{d}\)10\(^{m}\)00\(^{s}\) to −68\(^{d}\)5\(^{m}\)00\(^{s}\)). At (R.A., decl.) ∼ (5\(^{h}\)22\(^{m}\)30\(^{s}\), −67\(^{d}\)56\(^{m}\)00\(^{s}\)), an H\(_i\) cavity of an ~20 pc radius is seen. It is suggested that the H\(_i\) cavity indicates dynamical effects of stellar
Figure 4. (a) HI total intensity map toward N44. The integration velocity range is $V_{\text{offset}} = -109.8-89.7$ km s$^{-1}$. Position-velocity diagrams along lines A, B, and C passing through the east, center, and west, respectively, of the N44 region are demonstrated in Figure 6. (b) Enlarged Hα image of the N44 region. The image is Hα (MCELS, Smith & MCELS Team 1999). The red asterisks, pink crosses, and blue diamonds indicate WR stars, O-type stars (Bonanos et al. 2009), and SNRs (Maggi et al. 2016), respectively.

Figure 5. Typical spectra of HI at (a) (R.A., decl.) = (5h22m59.23, $-67^\circ55^\prime2^\prime$12) and (b) (R.A., decl.) = (5h22m23.20, $-68^\circ6^\prime9^\prime$02). The velocity ranges of the shaded area correspond to the integration ranges as shown in Figure 7.

Figure 6. The HI decl.-velocity diagrams along lines A, B, and C in unit of K degree. The integration is in R.A. over the range from 80°68 to 80°91 for (a), 80°45 to 80°68 for (b), and 80°22 to 80°45 for (c). The lowest contour level and intervals are 0.7 K deg. and 0.7 K deg., respectively. Black dashed lines indicate the position of N44 C. The white boxes in (a), (b), and (c) indicate the positions of bridge features.
winds and supernova explosions (Kim et al. 1998a). There is only the D component within \( \sim 60 \) pc of the HI cavity.

3.6. Physical Properties and the Distribution of Massive Stars

We calculate the mass and column density on the assumption that HI emission is optically thin. We use the equation as follows (Dickey & Lockman 1990):

\[
N_{\text{H}1} = 1.8224 \times 10^{18} \int \Delta T_b dv \text{ (cm}^{-2})
\]

where \( T_b \) is the observed HI brightness temperature (K).

The physical properties of HI gas along lines A, B, and C (width: \( \sim 70 \) pc; length: \( \sim 360 \) pc) shown in Figure 10 are summarized in Table 1. We integrated all of the velocity range \( -100.1 \text{ km s}^{-1} < V_{\text{offset}} < 89.7 \text{ km s}^{-1} \) for estimating the mass and column density of HI gas. The mass and column density of lines A, B, and C show similar values. The mass is about \( 10^6 \) \( M_\odot \), and the peak column density is about \( 6 \times 10^{21} \) cm\(^{-2} \). The velocity separations between the two velocity components in lines A, B, and C are about \( 20-60 \) km s\(^{-1} \). The bridge features are observed in lines A, B, and C. Most of the massive stars (WR and O-type stars) are located in line B. Figure 11 shows a histogram of the number of

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**Figure 7.** Integrated intensity distributions of HI for the three velocity components shown in Figure 3. The integration range is \( V_{\text{offset}} = -80.6 \) to \(-50.0 \text{ km s}^{-1} \) for (a), \(-50.0 \) to \(-15.6 \text{ km s}^{-1} \) for (b), and \(-15.6-9.7 \text{ km s}^{-1} \) for (c). The lowest contour level and intervals are 200 and 100 K km s\(^{-1} \) for (a), 500 and 150 K km s\(^{-1} \) for (b), and 1000 and 200 K km s\(^{-1} \) for (c). The symbols are the same as in Figure 4(c).
quantities around N44. We used Equation (in Figure 4.)

The number of WR and O-type stars located inside the areas of W belongs to the LMC. Because W have 2, 32, and 5 massive stars, respectively. We calculate the mass of the L, I, and D components toward the N44 region in Figure 10. Table 2 summarizes the physical quantities around N44. We used Equation (1) for the calculation of HІ parameters with the same method as in Table 1. The total mass is ~3.0 × 10⁶ M☉, and the mass of the D component occupies 2/3 of the total mass.

The H₂ gas mass was estimated by using the WCO−N(H₂) conversion factor (XCO = 7.0 × 10²² cm⁻² (K km s⁻¹)⁻¹, Fukui et al. 2008). We use the equation as follows:

\[ N(H_2) = X_{CO} \times W(12CO(J=1-0)), \]

where WCO is the integrated intensity of 12CO(J = 1 − 0) and N(H₂) is the column density of molecular hydrogen. The total mass of H₂ gas is ~3.0 × 10⁶ M☉. Most of the CO clouds are included in the D component.

3.7. Comparison with Dust Emission

We compared the intensity of HІ (W_HІ) and the dust optical depth at 353 GHz (τ_353) in order to investigate the gas-to-dust ratio. Figure 12 shows a typical spectrum of HІ (HI4PI Collaboration et al. 2016) toward the LMC. There is a Galactic foreground component at ~50 km s⁻¹ < V_LSR < +50 km s⁻¹, while the HІ emission in +150 km s⁻¹ < V_LSR < +350 km s⁻¹ belongs to the LMC. Because τ_353 does not have velocity information, we subtracted the foreground dust optical depth from τ_353 by assuming that the foreground HІ emission is optically thin and its W(HІ) is proportional to τ_353 using the W_HІ−τ_353 relation in the Galaxy (Fukui et al. 2015b) as follows:

\[ W_{HI}(K \text{ km s}^{-1}) = 1.15 \times 10^8(K \text{ km s}^{-1}) \times \tau_{353}. \]  

It is also possible to subtract the Galactic foreground by using a uniform Galactic foreground contamination using the averaged τ_353 value around the LMC. However, it is not appropriate to use the data around the LMC, because HІ gas is faint but widely extended around the LMC as in the Magellanic Bridge and Magellanic Stream (Putman et al. 1998). On the other hand, as shown in Figure 12, it is better to estimate the Galactic foreground from HІ data, since HІ gas can be clearly separated into the foreground component and LMC component by using velocity information. Figures 13(a) and (c) show the spatial distributions of τ_353 before and after subtracting the Galactic foreground, respectively. In addition, the Galactic foreground is considerably weaker than the LMC component, so the subtraction is made fairly accurately. The Galactic foreground accounts for 30% or less of the total τ_353 in the main regions of the LMC (Figures 13(b), and (d)).

First, we smooth the spatial resolution of HІ to the same resolution as τ_353, 5', and subtract the foreground from the total τ_353 for each pixel. We use only the LMC component for a comparison between the HІ data and τ_353 after the subtraction of the foreground component. Figure 14 shows a scatter plot of W_HІ and τ_353 for each pixel. The gray diamonds and red circles indicate the data points of the bar region (Paper I) and N44 region (Figure 4(a)), respectively. The values of τ_353 in the LMC are small (< 10⁻³), and the dust emission is optically thin. Therefore, τ_353 reflects the column density of hydrogen atoms and is proportional to W_HІ under the assumptions of (I) HІ emission is optically thin, (II) dust mixes well with gas, and (III) dust optical properties are uniform. On the other hand, saturation of W_HІ is caused when the atomic gas becomes colder and denser. It is thought that HІ is optically thin at high temperatures because the absorption coefficient of the HІ emission is inversely proportional to the spin temperature. We use HІ data that keep a proportional relation between W_HІ and τ_353. In this paper, we assumed that HІ gas is optically thin for the data points if T_d is high (22–24.5 K). Dust temperature (T_d) varies from region to region. So, we used HІ gas at T_d > 22.5 K in the bar region and HІ gas data for T_d > 24.5 K in the N44 region.

The ratio of W(HІ)/τ_353 is an indicator of the gas–dust ratio under the above assumptions of Sentences of (I)–(III). We derived the slope between W(HІ) and τ_353 by the least-squares fit, which is assumed to have a zero intercept. The black and red lines in Figure 14 indicate the fitting results of the bar and N44 regions, respectively. The slope of the bar region is 7.6 × 10⁷ K km s⁻¹, and that of the N44 region is 1.0 × 10⁸ K km s⁻¹, showing the difference of slopes by a factor of 1.3. This implies that the metallicity in the N44 region is lower than that in the bar region, a trend similar to the HІ ridge (Paper I). This result is discussed in Section 4.3. The dispersion of the bar region looks larger than that of the N44 region. This means that there may be a metallicity gradient in the bar region. We will present the detailed gas-to-dust ratio of the whole LMC in a following paper (K. Tsuge et al. 2018, in preparation).
4. Discussion

4.1. Evidence for the Collision of HI between the Two Velocity Components

We revealed the spatial and velocity distributions of the L ($V_{\text{offset}} = -80.6$ to $-50.0\ \text{km}\ \text{s}^{-1}$), I ($V_{\text{offset}} = -50.0$ to $-15.6\ \text{km}\ \text{s}^{-1}$), and D ($V_{\text{offset}} = -15.6$ to $+14.9\ \text{km}\ \text{s}^{-1}$) components by using high-resolution H I data. These results show the signatures of collision toward N44 between the H I flows in a similar fashion for the H I ridge and R136 in Paper I.

In Paper I, it was shown that the L ($V_{\text{offset}} = -100.1$ to $-30.5\ \text{km}\ \text{s}^{-1}$) and D components ($V_{\text{offset}} = -10.4$ to $+9.7\ \text{km}\ \text{s}^{-1}$) had the complementary spatial distribution at a kpc scale. It was also noted that the L and D components are connected by the bridge features in velocity space. These results give evidence of collision between the L and D components, suggesting that the collision of the H I gas triggered the formation of $\sim$400 O / WR stars in the H I ridge, which includes R136, N159, and the other active star-forming giant molecular clouds (Paper I). The observational signatures of high-mass star formation by colliding H I flows are characterized by three elements: (1) the two velocity components with a supersonic velocity separation, (2) the bridge features that connect the two velocity components in velocity...
Notes.

a Peak values in each line.

b Total number of O-type and WR stars.

Table 1

| Region  | Total Mass $(10^5 M_\odot)$ | $N$(H I)$^a$ $(10^{21} \text{ cm}^{-2})$ | Velocity Separation (km s$^{-1}$) | I component (Bridge Feature) | No. of Massive Stars$^b$ |
|---------|-----------------------------|----------------------------------------|----------------------------------|-----------------------------|------------------------|
| Line A  | 8.1                         | 5.6                                    | ~60                              | Yes                         | 2                      |
| Line B  | 9.0                         | 5.9                                    | ~20                              | Yes                         | 32                     |
| Line C  | 8.1                         | 5.7                                    | ~60/~20                          | Yes                         | 5                      |

Figure 10. Intensity map of H I consisting of three velocity components around N44. The image indicates the D component (−15.6 to 14.9 km s$^{-1}$). The blue and green contours indicate the L and I components, respectively. The contour levels and symbols are the same as in Figure 7. The light-blue shaded areas indicate the integrated intensity map of CO ($>$3$\sigma$ (3.5 K km s$^{-1}$); Wong et al. 2011) with the integration range of $V_{\text{offset}} = -109.8$ to 89.7 km s$^{-1}$.

4.1.2. The Bridge Features in Velocity Space

As seen in Figure 6, there is a component between the two velocity components. These signatures indicate that the two velocity components interact dynamically with each other in spite of a large velocity separation, which otherwise may suggest a large spatial separation and no interaction between the two in space.

4.1.3. Complementary Spatial Distribution

We revealed the detailed spatial distributions of the L, I, and D components and compared their spatial distributions. In Figure 9, the complementary spatial distribution is found not only between the L and D components (Figure 8) but also between the I and D components, whereas the I component partly overlaps the D component (Figure 9(a)). In Figure 8, the L and D components show complementary spatial distribution. The L component is distributed clearly along the edge of the D component in the northeast and southwest of N44. The I and D components show some complementary spatial distribution, while the I component partly overlaps with the D component in the south of N44 D, as shown in Figure 9(b).

A possible interpretation of these spatial distributions is deceleration of the H I gas by momentum conservation in the interaction. In the R136 region, we interpreted that the L component penetrated into the D component with small deceleration when the D component has lower column density than the L component, whereas the L and D components merge together with significant deceleration where they have nearly the same column density. The difference in the column density of colliding H I flows then affects the velocity in the merged

4.1.1. The Supersonic Velocity Separation

In N44, the velocity separation of the two components is about 30–60 km s$^{-1}$ (Figure 5). If we consider a projection effect, the actual velocity separation is larger than observed. These large velocity separations cannot be explained by the stellar winds and UV radiation from the high-mass stars, where the typical stellar feedback energy is less than 10% of the kinematic energy of the colliding flows (Paper I). As we mentioned in Section 1.3, Kim et al. (1998a) found that there are two clear intensity depressions of H I gas and expanding shells of H I gas by small-scale (hundreds of pc) analysis (shown in Figures 2 and 4 of their paper). However, we did not find obvious expansion structures in a kpc-scale analysis (Figure 6). Figure 15 shows the second-moment map of the D component (−15.6 km s$^{-1}$ < $V_{\text{offset}} < +14.9$ km s$^{-1}$). The average velocity dispersion is ~7.6 km s$^{-1}$, and there is no spatial correlation between the H$\alpha$ shell (dashed circle) and velocity dispersion (Figure 15(a)). Moreover, it is impossible to explain the motion of the L, I, and D components by expanding the shell from the compact area of energy supply. We calculated the kinematic energy of the H I gas as ~10$^{53}$ erg by assuming that the expansion velocity is 30 km s$^{-1}$. So, the kinematic energy of a superbubble is insufficient to explain the velocity distribution of the H I gas. Moreover, it requires ~2000 supernova explosions within the age of N44 if we assume that kinematic energy injection by supernova explosions is transferred in gas acceleration by ~5% (Kruisen et al. 2012). This number of supernova explosions is much larger than ~300, which is expected from the scale of the superbubble N44 (Meaburn & Laspias 1991).

On the other hand, it is seen that the velocity dispersion of the D component increases toward the region where the I component is located, as shown in Figure 15(b). This suggests that the collision between H I flows played a role in creating the observed gas motion.

Notes.

a Peak values in each line.

b Total number of O-type and WR stars.
components by momentum conservation (Paper I). If we assume a similar collisional process, the distributions of HI gas can be interpreted as follows. In the northeast and southwest of N44, two parts of the L component are located where the intensity of the D component is weaker than the surroundings (Figure 8). The average column density of the D component in this region is $\sim$1.7 x 10$^{-21}$ cm$^{-2}$. It is likely that the L component weakly exhibits a sign of deceleration, because the $N$(HI) of the L component dominates that of the D component when momentum conservation is considered. The initial column density of the L component was probably high enough toward the region. In the south of N44, the I component overlaps with the D component, which has the highest intensity of HI (Figure 9(a)). The maximum column density of the D component is $\sim$4.0 x 10$^{-21}$ cm$^{-2}$. We suggest that the $N$(HI) of the L and D components was nearly the same, and that the collision resulted in merging of the two components at an intermediate velocity of these components. The total $N$(HI) of the merged component was then elevated to $\sim$6 x 10$^{-21}$ cm$^{-2}$ due to the merging. In the other regions, the I and D components show complementary spatial distribution, a characteristic of collision between the two components. The I component exists but is weak in HI in the north of N44 B and C, as shown in Figure 9(a). This is probably because the stellar ionization already dispersed the collisional HI gas. The age of N44 (5–6 Myr; Will et al. 1997) is three times older than that of R136. We suggest that the two components are also colliding in the other areas of N44.

Another possible interpretation is displacement of the colliding two-velocity components. It is usually the case that the angle of the colliding two clouds is not 0$^\circ$ relative to the line of sight. This collision angle $\theta$ makes a displacement of the complementary distribution between the intensity depression of the D component and the dense part of the I component according to the time elapsed since the initiation of the collision. Thus, we are able to see the overlap of the I and D components in the south of N44 D shown in Figure 9(a), and the overlap is considered to be due to the projection. In Figure 9(b) where is applied a displacement of 107 pc as shown by an arrow. We see that the I component better fits the edge of the D component than in Figure 9(a), and they exhibit complementary distribution. In order to estimate the optimum displacement, we applied the method presented in Fukui et al. (2018d). We calculated the overlap integral $H(\Delta)$ in pc$^2$, which is a measure of the overlapping area of the strong I component (integrated intensity >550 K km s$^{-1}$) and the depression of the D component (integrated intensity <1100 K km s$^{-1}$).

We then searched for the best optimal solution of displacement to maximize the overlapping integral $H(\Delta)$ sweeping the I component in position as a cross-correlation function. The sweeping was done toward five different directions of the $\Delta$ axis with a position angle from 170$^\circ$ to 190$^\circ$ with 5$^\circ$ steps and by the $\Delta$ offsets from −400 to +400 pc with 9.7 pc steps. It was then found that the $\Delta$ axis of 180$^\circ$ and $\Delta = 107$ pc gives the largest $H(\Delta)$ value, as shown in Figure 9(c). This displacement is indicated in Figure 9(b) by the arrow and by the good complementary distributions between the strong I component and the depressed D component. More details about $H(\Delta)$ are given in the Appendix of Fukui et al. (2018d).

The I component partly overlaps with the D component, for example, at (R.A., decl.) $\sim (5^h25^m00^s, -68^d20^m00^s)$, after applying the displacement. We note that the complementary distribution may not hold so strictly, depending on the three-dimensional spatial distributions of the D component, and that the I component may overlap the D component in part, depending on the initial distribution of the two components.

These characteristics (Sections 4.1.1–4.1.3) are consistent with the observational signatures of collision between the HI

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**Table 2**

| Component | Mass of Hydrogen Gas | Mass of the I Component | Mass of the D Component | Total Mass |
|-----------|----------------------|-------------------------|-------------------------|------------|
| H I       | $1.1 \times 10^7$ M$_\odot$ | $5.3 \times 10^2$ cm$^{-2}$ | $2.0 \times 10^6$ cm$^{-2}$ | $3.0 \times 10^6$ cm$^{-2}$ |
| CO        | $1.1 \times 10^7$ M$_\odot$ | $1.0 \times 10^5$ cm$^{-2}$ | $2.4 \times 10^6$ cm$^{-2}$ | $3.0 \times 10^6$ cm$^{-2}$ |

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**Figure 11.** Histograms of the number of massive stars. The horizontal and vertical axes are R.A. and the number of massive stars located within each R.A. bin, respectively. The histograms of the number of WR stars and O-type stars and the total number of massive stars are shown by red and blue shaded areas and the open area, respectively.
flows shown in Paper I and lend support that the colliding H I flows triggered the formation of \(\sim 40\) high-mass stars in N44 as in the R136 region.

4.2. Stellar Properties and Crossing Timescale

In the previous section, we presented a scenario for massive star formation by colliding H I flows in N44. In this subsection, we discuss the stellar properties, star formation rate, and crossing timescale in the context of the scenario. Crossing timescale is the time it takes for the L or I components to pass through the D component in collision.

4.2.1. Distribution of High-mass Stars and Physical Properties of H I Gas

In Figure 10, we see that most of the high-mass stars are formed in the central region of N44 where H I flow is colliding (line B in Figure 10). We suggest that the high-mass stars were mostly formed by colliding H I flows in line B, if H I flows are decelerated by the collision and become further compressed. In the decl.–velocity diagrams of the central region of N44 (Figure 6), the velocity separation between the two components in line B is smaller than that in lines A and C, where the velocity separation is \(\sim 50\) km s\(^{-1}\), while in line B, the velocity separation is \(\sim 20\) km s\(^{-1}\). This difference in the velocity separation suggests that the L component is significantly decelerated by the collision with the D component in line B, leading to the most significant H I gas compression.

We calculated the total H I mass and peak column density in lines A, B, and C in Figure 10 and did not find a significant difference among the regions, which suggests that the current total \(N(H I)\) is similar toward the three lines. The age of N44, 5–6 Myr (Will et al. 1997), makes it difficult to see the initial conditions prior to the collision because the H I gas was significantly dissipated by the high-mass stars in 5–6 Myr. The H I gas within 25–30 pc of high-mass stars is dispersed by ionization and stellar winds at an empirical velocity of the ionization front of \(\sim 5\) km s\(^{-1}\) observed in Galactic high-mass clusters (Fukui et al. 2016), and the amount of the H I gas in line B may be less than the initial value. Thus, the H I gas was possibly more concentrated in line B than lines A and C before the collision. A scenario that the H I gas was further compressed and high-mass stars formed in line B is consistent with the observations.

We also estimated the total interstellar medium mass of the star-forming region N44, as illustrated by a white dashed circle in Figure 4(b). The region is determined so that it includes the H\alpha bubble. The mass of H I is estimated to be \(\sim 5 \times 10^5 M_\odot\) by assuming a uniform column density of \(\sim 6.0 \times 10^{21} \text{cm}^{-2}\) (see Table 3), and the total mass of H\(_2\) is \(\sim 5 \times 10^5 M_\odot\) using Equation (2). We calculated the approximate total stellar mass of N44 \((M^*)\) as \(\sim 1.0 \times 10^5 M_\odot\), assuming the initial mass function (IMF) as follows. The IMF varies with the mass range of the star (Kroupa 2001) as follows: \(\phi(M) \propto M^{-2.3}\); \(M > 0.5 M_\odot\), \(\phi(M) \propto M^{-1.3}\); \(M > 0.5 M_\odot\); \(0.08 M_\odot < M < 0.5 M_\odot\), \(\phi(M) \propto M^{-0.3}\); \(M > 0.08 M_\odot\), \(0.01 M_\odot < M < 0.5 M_\odot\), \(\phi(M) \propto M^{-1.3}\); \(M < 0.01 M_\odot\). When the stellar mass is larger than \(0.5 M_\odot\), we adopt \(\alpha = 2.37\) as the slope of the IMF obtained from BV photometry (Will et al. 1997), and we adopt \(\alpha = 1.37\) as the slope of the IMF for a stellar mass less than \(0.5 M_\odot\) (Kroupa 2001). The star formation efficiency (SFE) is about 10\% for the total interstellar mass \((M(H I+H_2))\), where we define SFE as \(M^*/(M^*+M(H I+H_2))\).

4.2.2. Crossing Timescale of Collision

We found a spatial displacement between the I and D components shown in Figure 9(b). We obtained the projected displacement to be 107 pc at a position angle of 180\(^\circ\), and the velocity separation is 20 km s\(^{-1}\) from Figure 5. More details are given in Section 4.2.1. The crossing timescale is estimated to be \(\sim 150\) pc/28 km s\(^{-1}\) \(\sim 5\) Myr by assuming the angle of the cloud relative motion to the line of sight to be \(\theta = 45\(^\circ\)\). The crossing timescale is consistent with the age of N44 (Will et al. 1997).

We also estimated the crossing timescale of the collision from a ratio of the cloud size and the relative velocity between the two
clouds. The apparent spatial extent of the colliding clouds forming high-mass stars is about 200–300 pc in Figure 7(c). The velocity separation is \( \sim 28 \text{ km s}^{-1} \) if we assume that the relative motion between the two clouds has an angle of 45°. We calculated a ratio of the cloud size to the relative velocity, giving \( \sim 7–10 \text{ Myr} \) as the crossing timescale. The timescale gives a constraint on the upper limit for the age of the high-mass stars formed by colliding HI flows. From these results, we suggest that the crossing timescale is 5–10 Myr, while a younger age is more likely because the deceleration tends to lengthen the timescale more than the actual value.

### 4.3. Inflow of the Metal-poor Gas from the SMC

We found evidence of HI gas inflow from the SMC from the HI and Planck/IRAS data (Paper I) and suggest that the HI gas of the SMC is possibly mixed with the HI gas of the LMC by the tidal interaction. Specifically, we derived a gas–dust ratio from a scatter plot between the dust optical depth at 353 GHz (\( \tau_{353} \)) and the 21 cm HI intensity (\( W(\text{H}I) \)) in the LMC. We used the data with the highest dust temperature, which are probably optically thin HI emission (Fukui et al. 2014b, 2015b). The slope of the N44 region in the plot is steeper by \( \sim 30\% \) than that of the bar region, which is an older stellar
system than the HI ridge. This difference is interpreted as due to different dust abundance between them.

The results of numerical simulations (Bekki & Chiba 2007b) show that the HI gas of the SMC was mixed with the LMC gas by the close encounter that happened 0.2 Gyr ago. If a mixture of the SMC and LMC gas was triggered by the tidal interaction, the N44 region should contain the low-metallicity HI gas of the SMC. If the HI gas of the N44 region consists of the HI mass of both the SMC and the LMC at a ratio of 3:7 by assuming a subsolar metallicity of $1/10 Z_{\odot}$ in the SMC (Rolleston et al. 2003) and $1/2 Z_{\odot}$ in the LMC (Rolleston et al. 2002), the different slopes in Figure 14 are explained by the mixing. This scenario deserves further pursuit by more elaborate numerical simulations of the hydrodynamical tidal interaction in detail.

4.4. Comparison with the HI Ridge and HI Ridge Including R136

We compared the physical parameters of N44 and the HI ridge as summarized in Table 3. We see the different physical conditions and the activity of high-mass star formation between N44 and the HI ridge. The HI ridge contains the massive stars of R136 in the core of 30 Doradus. The number of high-mass stars of N44 is 10% of the HI ridge (Doran et al. 2013), and the HI intensity of the L component toward N44 is 25% of the HI ridge. The spatial extent of the colliding HI flow of N44 is $\sim$25% of the HI ridge. In addition, we find the I component toward N44, which has a smaller velocity separation than the L component.

Furthermore, the timescale of the collision is different between N44 and R136. The crossing timescale of N44 is 5–6 Myr, but that of R136 is $\sim$3 Myr (derived from Paper I). This difference may have been caused by a difference in the timing of the inflow impact of the tidally driven SMC gas (Bekki & Chiba 2007b).

From these results, we speculate that some physical parameters of the collision, for instance, the amount of the inflow gas from the SMC and the velocity of the collision, determine the activity of high-mass star formation. However, it is not understood which parameter is important, because we do not have a large number of observational examples and appropriate numerical simulations of the colliding HI flows. We need to study other star-forming regions in the LMC as shown in Figure 3 and carry out statistical analyses more extensively in future work.

5. Conclusion

The main conclusions of the present paper are summarized as follows.

1. We analyzed the high spatial resolution HI data ($1''$; corresponding to $\sim$15 pc at the distance of the LMC) observed by the ATCA and Parkes telescopes (Kim et al. 2003) and revealed the spatial and velocity

![Figure 14](image-url) Scatter plot of $W(\text{HI})$ against $\tau_{353}$. The red points are the data with $T_{d} \geq 24.5$ K in the N44 region (the region of Figure 1(a)), while the gray points are the data with $T_{d} \geq 22.5$ K in the bar region (Paper I). The red and black lines denote the results of the least-squares fits assuming zero intercept toward N44 and the bar regions, respectively.

| Object | No. of O/WR Stars | Age (Myr) | Spatial Extent of Colliding HI Gas | Fraction of SMC Gas (max) ($10^{22}$ cm$^{-2}$) | Total HI Mass ($M_{\odot}$) |
|--------|------------------|-----------|-----------------------------------|---------------------------------|----------------------|
| HI ridge | $\sim$400 | 1.5–4.7 | $\sim$1 kpc $\times$ 2.5 kpc | 0.5 | 1.0 | $1.0 \times 10^{8}$ |
| N44 | $\sim$40 | 5–6 | $\sim$800 pc $\times$ 800 pc | 0.3 | 0.6 | $2 \times 10^{7}$ |

![Table 3](image-url) Comparison of N44 with HI Ridge Including R136
distributions of N44. We confirmed that the two H I components at different velocities, the L and D components (Fukui et al. 2017a), are colliding at a 500 pc scale with a velocity difference of ~30–60 km s\(^{-1}\). The collision is characterized by the spatial complementary distribution and bridge features in velocity space. In addition, we newly defined the I (intermediate) component between the two velocities as a decelerated gas component due to the collision.

2. We calculated the total mass of massive stars (WR and O-type stars) and H I gas and derived the SFE in N44 to be ~10% from a ratio of (the stellar mass)/(the stellar mass plus the H I and CO mass). A timescale of the collision is estimated by the displacement of the I component and the velocity difference. We estimated that ~5 Myr passed after the collision by assuming that the I component moved by ~100 pc in projection at a velocity of 20 km s\(^{-1}\). This timescale is consistent with the age of the star-forming region in N44 (Will et al. 1997). These results suggest that it is possible that the high-mass stars in N44 were formed by triggering in the colliding H I flows.

3. We found that the L component is metal-poor, as indicated by the low dust optical depth. We estimated the metal content by a comparison of dust optical depth at 353 GHz (\(\tau_{353}\)) measured by Planck/IRAS and the intensity of H I (W(H I)). We derived an indicator of the gas–dust ratio (W(H I)/\(\tau_{353}\)) by least-squares fitting, which is assumed to have a zero intercept. The gas–dust ratio (W(H I)/\(\tau_{353}\)) of N44 is 30% larger than that of the bar region. If the N44 region consists of H I mass from the SMC (1/10 \(Z_\odot\); Rolleston et al. 2003) and LMC (1/2 \(Z_\odot\); Rolleston et al. 2002) at a ratio of 3:7, the slopes different by 30% in Figure 14 are explained. This result supports the tidal origin of the H I flow and mixing of the SMC gas with the LMC gas as theoretically predicted (Bekki & Chiba 2007b). The H I ridge is mixed by the H I gas of the SMC and LMC at a ratio of 1:1 (Paper I), and it means that the influence of the tidal interaction was weaker in N44 than in the H I ridge. The larger dispersion of the scatter plot between \(\tau_{353}\) and W(H I) in the bar region could be the result of metal enrichment by star formation history. A more detailed study of the gas-to-dust ratio for the entire LMC will be presented in an upcoming paper (K. Tsuge et al. 2018, in preparation).

4. We compared a collision size scale of the N44 region and that of the H I ridge and found that the collision of the N44 region is of a smaller scale than that of the H I ridge. Specifically, the spatial extent of the colliding H I flow is about 1/4 that of the H I ridge, and the intensity of the L component is weaker by 1/4 than that of the H I ridge. It is clearly seen in N44 that the spatial scale of collision, intensity of blueshifted H I gas, number of formed massive stars, and H I mass of the inflow from the SMC are smaller than in the H I ridge.

5. We discussed a scenario that a tidally driven colliding H I flow triggered the formation of high-mass stars based on the present results. The blueshifted H I components (the L and I velocity components) were formed by tidal stripping between the LMC and SMC about 0.2 Gyr ago (Bekki & Chiba 2007a). The perturbed H I gas is colliding with the H I gas in the LMC disk at present. This collision formed ~40 O/WR stars in N44 by the same mechanism as in the R136 region (Paper I), but the number of high-mass stars of N44 is ~1/10 as compared with that in R136. The spatial scale of collision and the H I intensity of the blueshifted components are smaller than H I ridge, probably because the tidal interaction between the LMC and SMC was weak in the N44 region. More details of the collision are yet to be better clarified for understanding the cause of the difference, and we need to increase the number of cases where the colliding H I flows trigger high-mass star formation in the LMC.
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Appendix A  
Decompositions of the L and D Components of HI

To decompose the L and D components of HI in the LMC, we used the following method.

1. Verification of spectrum. We investigated the velocity structures of the HI spectra of the whole LMC by eye. We found that the HI spectra are dominated by a single-peaked component, with multiple components distributed in some regions.

2. Spectral fitting.
   (a) Search for a velocity channel that has the strongest intensity of the HI spectrum (Figure 16(a)). We define the emission peak with a brightness temperature higher than 20 K as the significant detection.
   (b) Fit the HI profile to a Gaussian function. The velocity range used for the fitting is ±10 channels (≈16.5 km s⁻¹) with respect to the central velocity shown in Figure 16(a).
   (c) The fitting was performed to a single Gaussian distribution as follows:

\[
f(x) = A_0 \exp \left( -\frac{(v - v_0)^2}{2\sigma^2} \right)
\]

where \(A_0\), \(v_0\), and \(\sigma\) are the height, central velocity, and velocity dispersion of the Gaussian, respectively, set to be free parameters.

(d) Subtract the Gaussian distribution obtained by (b) from the original HI spectrum as the residual shown in Figure 16(b).

(e) Repeat steps (a)–(d) for each spectrum twice.

3. Comparison of the peak velocity.

We compared the central velocities of the first and second peaks we identified with the above steps for each pixel and defined the L component as the component having lower velocity and the D component as having higher velocity. If the above procedure only gives a single velocity component, it is attributed to the D component. Then, we obtained the central velocity distributions of the L and D components.

The velocity distribution of the D component indicates the rotation of the LMC (Figure 17(a)). However, we see some local velocity structures differing from the galaxy rotation perturbed by supernova remnants, superbubbles, and supergiant shells. So, we took the mean velocity of the 500 pc × 500 pc area by using the median filter for each pixel to remove these influence. Figure 17(b) shows the smoothed rotation velocity map of the LMC. The disk of the LMC rotates to the west from the east, and this result is consistent with that of Kim et al. (2003).

4. Subtraction of the galactic rotation velocity.

To obtain the velocity relative to the disk rotation velocity (\(V_{\text{offset}}\)) for each pixel, we subtracted the smoothed radial velocity of the D component (\(V_D\)) from the original velocity (\(V_{\text{LSR}}\)) by shifting the velocity channels:

\[
V_{\text{offset}} = V_{\text{LSR}} - V_D
\]
Appendix B
Rotation Curve of the D Component

Here we describe the method of deriving the rotation curve of the LMC using the radial velocity map of the D component as shown in Figure 14(b).

1. Magellanicocentric radial velocity field.

First, we subtract the system velocity of the LMC from the radial velocity of the D component for each pixel and define $V_{\text{Magellan},ij} = V_{ij} - V_{\text{sys}}$, where $V_{\text{Magellan},ij}$ is the Magellanicocentric radial velocity of the D component, $V_{ij}$ is the peak velocity of the D component at the pixel position, and $V_{\text{sys}}$ is the system velocity of the LMC of 252.5 km s$^{-1}$. The suffix of $(i, j)$ denotes the coordinates along the major and minor axes in Figure 2(b).

2. Rotation velocity field.

The LMC is almost a face-on galaxy, but it has some inclination angle between the plane of the sky and the plane of the galaxy disk. So, we compensate for the velocity gradient due to the inclination. We derive a rotation velocity $V_{\text{rot}}(R_{ij})$ at the radius of $R_{ij}$ by using the equation (Weaver et al. 1977)

$$V_{\text{rot}}(R_{ij}) = \frac{V_{\text{Magellan}}}{\cos \theta_{ij} \sin I},$$

where $R_{ij}$ is the radius from the center on the plane of the galaxy given as $R_{ij} = \sqrt{x^2 + (y / \cos I)^2}$, and $I$ is the

---

**Table 4**
Results of the Rotation Curve Fittings

| P.A. (deg) | Inclination (deg) | $\chi^2$/d.o.f | P.A. (deg) | Inclination (deg) | $\chi^2$/d.o.f |
|------------|------------------|---------------|------------|------------------|---------------|
| 190        | 38               | 1.279         | 200        | 38               | 0.965         |
| 37         | 1.259            | 37            | 37         | 1.246            | 36            |
| 36         | 1.248            | 36            | 35         | 1.248            | 35            |
| 34         | 1.259            | 34            | 33         | 1.275            | 33            |
| 32         | 1.296            | 32            | 195        | 38               | 1.208         |
| 37         | 1.189            | 37            | 36         | 1.181            | 36            |
| 35         | 1.190            | 35            | 34         | 1.218            | 34            |
| 33         | 1.261            | 33            | 32         | 1.329            | 32            |

**Table 5**
The Best-fit Kinematic Parameters of the Rotation Curve

| Parameter                    | Value          |
|------------------------------|----------------|
| Kinematic center (R.A., decl.) | 05°16′24.82, −69°05′58.88 |
| P.A. of major axis (deg)      | 200            |
| Inclination (deg)             | 35             |
| $V_{\infty}$ (km s$^{-1}$)    | 61.1           |
| $R_0$ (kpc)                   | 0.94           |
| $V_{\text{sys}}$ (km s$^{-1}$) | 252.5          |

**Table 6**
$\chi^2$ Fitting Results with Different Sizes of the Median Filter

| Filter Size | $\chi^2$/d.o.f |
|-------------|---------------|
| 50 pc × 50 pc | 1.518         |
| 200 pc × 200 pc | 1.267         |
| 350 pc × 350 pc | 0.974         |
| 500 pc × 500 pc | 1.007         |
| 650 pc × 650 pc | 1.039         |
| 800 pc × 800 pc | 0.971         |
| 950 pc × 950 pc | 0.743         |

Note. Cols. (1) and (3): position angle of major axis. Cols. (2) and (4): inclination of rotation axis to the line of sight.
3. Mask of the region.

We masked the regions not used for deriving the rotation curve, shown as the shaded regions in Figure 2(b). The majority of the velocity fields follow a flat disk rotation (Figure 2(a)). However, there are some regions with velocities deviating from the galaxy rotation. This trend is also suggested by Luks & Rohlfs (1992). In order to minimize the local disturbances, we mask the regions with $V_{rot} \geq 120 \text{ km s}^{-1}$. In addition, a $|\theta| < 5^\circ$ sector around the major axis is also masked, because the rotation velocity cannot be determined.

The locally disturbed regions are roughly located at the southeast arm (the H I ridge region) and the northwest arm end. Their distributions are consistent with the spatial distribution of tidally interacting gas between the LMC and SMC calculated by Bekki & Chiba (2007a; see also Figure 4 of Bekki & Chiba 2007a). Thus, it is suspected that the local disturbances are due to the tidal interaction.

4. Derivation of rotation curve.

We divide the whole region into 16 elliptical annuli whose widths are 0.25 kpc (white ellipses in Figure 2(c)). We plot the average rotation velocity ($V_{rot}$) for each annulus as a function of the deprojected radial distance $R_{ij}$ on the plane of the galaxy from the kinematic center of the LMC (red plus sign in Figure 2(b)). The error bar in $R_{ij}$ is the width of the annulus, and that in $V_{rot}$ is given as the standard deviation of the rotation velocity in the annulus.

5. Fitting to the flat rotation model.

We fit the plotted data to the flat rotation model expressed as the tanh function in the following equation (Corbelli & Schneider 1997):

$$V_{rot}(R_{ij}) = V_\infty \tanh(R_{ij}/R_0),$$

where $R_0$ is the radius where the velocity field changes from rigid to flat rotation, and $V_\infty$ is the circular velocity at $R_{ij} \gg R_0$.

There are many previous studies of the LMC kinematics, as reviewed by Westerlund (1990). Nevertheless, the position angle of the major axis and the galaxy inclination are not well determined. The estimated position angles are in the range $\sim 168^\circ$–$220^\circ$ with an inclination of $30^\circ$–$40^\circ$. We decide the best-fit values making the reduced $\chi^2$ value given by the rotation curve fittings closest to unity by changing the values of the position angle and inclination, as listed in Table 4.

In addition, we change the value of $V_\infty$ by 0.5 step between 245 and 260 km s$^{-1}$, and the best-fit value is 252.5 km s$^{-1}$. We also optimized the kinematic center of the LMC (R.A., decl. = $05^h 17^m 6$, $-69^\circ 2^\prime 0$). We change the center position by a 1$’$ step in a region $\pm 4’$ from the center by Kim et al. (1998b) and obtain the best-fit value of (R.A., decl.) = ($05^h 16^m 24^s 8$, $-69^\circ 05^\prime 58^\prime 9$). We summarized the best-fit parameters of the kinematic of the LMC in Table 5. The final rotation curve derived by this study is shown in Figure 2(c).

6. Median filter.

When we subtract the radial velocity of the D component, smooth the velocity field by median filter as described in Appendix A, with the size of the median filter optimized as follows. We change the size from 50 pc × 50 pc to 950 pc × 950 pc and adopt the 500 pc × 500 pc size as the best choice in this study, based on the value of the reduced $\chi^2$ closest to 1 (Table 6).

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