Discovery of a Molecular Collision Front in Interacting Galaxies NGC 4567/4568 with ALMA

Hiroyuki Kaneko (金子雄之)1,2, Nario Kuno (久野成之)3,4, and Takayuki R. Saitoh (斎藤貴之)5

1 Nobeyama Radio Observatory, 462-2, Nobeyama, Minamimaki, Minamisaku, Nagano, 384-1305, Japan; kaneko.hiroyuki@nao.ac.jp
2 National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo, 181-8588, Japan
3 Graduate School of Pure and Applied Sciences, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki, 305-8577, Japan
4 Toyonaga Center for the History of the Universe, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8571, Japan
5 Earth-Life Science Institute, Tokyo Institute of Technology, 2-12-1, Ookayama, Meguro, Tokyo, 152-8550, Japan

Received 2018 March 30; revised 2018 May 23; accepted 2018 May 28; published 2018 June 13

Abstract

We present results of 12CO(J = 1–0) imaging observations of NGC 4567/4568, a galaxy pair in a close encounter, with the Atacama Large Millimeter/Submillimeter Array (ALMA). For the first time, we find clear evidence of a molecular collision front with a velocity dispersion that is 16.8 ± 1.4 km s⁻¹ at the overlapping region, owing to high spatial and velocity resolution. By integrating over the velocity width that corresponds to the molecular collision front, we find a long filamentary structure with a size of 1800 pc × 350 pc at the collision front. This filamentary molecular structure spatially coincides with a dark lane seen in the R-band image. We find four molecular clouds in the filament, each with a radius of 30 pc and mass of 10⁸ M☉; the radii matching a typical value for giant molecular clouds (GMCs) and the masses corresponding to those between GMCs and giant molecular associations (GMAs). All four clouds are gravitationally bound. The molecular filamentary structure and its physical conditions are similar to the structure expected via numerical simulation. The filament could be a progenitor of super star clusters.

Key words: galaxies: evolution – galaxies: individual (NGC 4567/4568) – galaxies: interactions – galaxies: ISM – ISM: molecules

1. Introduction

The gravitational interactions of galaxies (collisions and mergers) play an important role in the evolution of galaxies. A close galaxy–galaxy interaction event greatly alters the distribution and kinematics of stars and gas, resulting in the formation of elliptical galaxies (Toomre 1977). During this phenomenon, significant enhancement of star formation activity is observed (Bushouse 1986). It is also known that the activation of star formation follows the progression of the interaction: while the star formation rate (SFR) in interacting galaxies during the early stage is only a few times higher than field galaxies, the SFR becomes 10⁶ times higher than field galaxies during the late stage of the interaction (Kennicutt et al. 1987; Teyssier et al. 2010). In particular, ultra-luminous infrared galaxies (ULIRGs; LIR > 10¹² L☉), most of which are thought to be in the late stage of the interaction (Clements et al. 1996), show bursts of star formation. High-resolution numerical simulations revealed that multiple nuclei in ULIRGs cannot only be made by multiple major mergers, but also a single merger, and produce massive and compact star clusters (Matsui et al. 2012). In spite of these findings from observations and simulations, the detailed mechanisms of active star formation in interacting galaxies, such as how off-center starbursts occur, are still unclear.

Because molecular gas fuels star formation, investigating how the interaction affects molecular gas properties is an important step for understanding the mechanism of the intense star formation in interacting galaxies. Previous molecular gas observations have mainly been focused on the interacting galaxies with starbursts (e.g., Whitmore et al. 2014; Saito et al. 2015). Although these observations can help us investigate the effects of starbursts on galaxies, how star formation activity is enhanced remains unexplained. In order to inspect how the interaction influences molecular gas properties, molecular gas observation of interacting galaxies at the early stage is crucial because they should maintain conditions before or at the beginning of active star formation, taking into account the timescale of star formation.

The NGC 4567/4568 pair is one of the ideal interacting galaxies for this purpose because of their alignment, vicinity (16 Mpc), and weakly enhanced star formation activity in their overlapping regions. Although stellar morphology is undisturbed, the NGC 4567/4568 pair is thought to be in the early stage from their asymmetric H1, 12CO(J = 1–0) (hereafter CO), and 12CO(J = 2–1) morphologies and smooth velocity field (Iono et al. 2005; Kaneko et al. 2013; Nehlig et al. 2016). H1 has a peak in their overlapping region, and CO distribution is also distorted toward the overlapping region. A fraction of the molecular gas mass to the total gas mass is higher in this pair than that in field galaxies, implying that the interaction already affects the molecular gas properties in this pair even during the early stage of the interaction (Nehlig et al. 2016; Kaneko et al. 2017). Furthermore, there are no starbursts in the overlapping region, but there are some large star-forming regions traced by Hα (Koopmann et al. 2001) and MIPS 24 μm (Smith et al. 2007). These facts indicate that the active star formation induced by the interaction has just commenced in this galaxy pair.
2. Observations

CO observations toward the NGC 4567/4568 galaxy pair were carried out as an ALMA Cycle 1 program (2012.1.00759.S). The 12.0 m array observations were performed using 36 antennas with the C32-4 configuration. The total observed time on source was 25.4 minutes, and 39 fields of view were required to cover a whole region of the galaxy pair. Bandpass and phase were calibrated with J1229+0203 (the observed flux: 6.3 Jy) and J1239+0730 (the observed flux: 0.87 Jy), respectively.

Observations with the Atacama Compact Array (ACA), which consists of ten 7 m antennas and twelve 12 m antennas for Cycle 1 observation, were also requested to image large-scale structures. The total on-source time for the ACA 7 m array observations was 20.9 minutes. The bandpass calibrator and the phase calibrator for the ACA 7 m array were J1058+0133 with the observed flux of 2.7 Jy and J1229+0203 with the observed flux of 5.9 Jy, respectively. While the ACA 7 m array observations were successfully completed, the ACA 12 m (total power) single-dish array observation was not performed for this program. Interferometric data without single-dish data has no sensitivity on a structure larger than \( \sim 0.6\lambda / L_{\text{min}} \), where \( L_{\text{min}} \) is the shortest projected baseline. For this reason, our Atacama Large Millimeter/Submillimeter Array (ALMA) data cannot detect emission from extended structures larger than \( \sim 20'' \) (corresponding to 1.55 kpc at 16 Mpc), as \( L_{\text{min}} \) is \( \sim 15 \) m for our observations. This scale is almost comparable to our previous single-dish data obtained with the Nobeyama 45 m telescope (Kaneko et al. 2013).

Data reduction including calibration and imaging was made with the Common Astronomy Software Applications package ver.4.2.1. The 12 m array data and the ACA 7 m array data were combined together, the continuum was subtracted, and then corrected for the primary beam attenuation. The imaging was done interactively using the CLEAN task with Briggs weighting (robustness parameter of 0.5). The final data were imaged on a 540 \( \times \) 648 pixel with a grid size of 0.5 pixels. The combined cube has an angular resolution of \( 2'' \times 2'' \) (equivalent to 155 pc \( \times \) 155 pc at 16 Mpc) and a velocity resolution of 5 km s\(^{-1}\), which is the highest spatial and velocity resolution ever obtained in molecular lines for this galaxy pair. Resultant rms noise is 8.5 mJy beam\(^{-1}\).

3. Results

A CO-integrated intensity map is shown in Figure 1. Each galaxy reveals molecular spiral arms and strong emissions at their galactic center. No strong emission is seen in the overlapping region, although the single-dish observations detect significant CO emission there. This implies the presence of extended structures. The total CO flux from the whole system obtained with the ALMA Cycle 1 observation is \( (1.29 \pm 0.20) \times 10^3 \) Jy km s\(^{-1}\). Because the data observed with the ALMA Cycle 1 program has less sensitivity for the extended structure as mentioned in Section 2, we estimated the missing flux by comparing to the data obtained with a single-dish telescope. CO imaging with the single dish was performed by our previous observations using the Nobeyama 45 m telescope. The CO flux of the NGC 4567/4568 system obtained with the Nobeyama 45 m telescope is \( (2.38 \pm 0.37) \times 10^4 \) Jy km s\(^{-1}\), meaning that the missing flux for the ALMA Cycle 1 observation reaches 46 \% of the total flux.

We made a position–velocity diagram (PVD) along with the red arrow in Figure 1 that crosses the two large star-forming areas in the overlapping region. The line is centered on (R.A., decl.) = \( (12^{h}36^{m}35^{s}6, 11^{\circ}15'15''/0) \) with a position angle of 50 degrees. If two galaxies are “apparently” in contact with the celestial sphere and not interacting physically, the PVD should have a gap in the velocity axis. Figure 2 illustrates, however, that molecular gas in NGC 4567 and NGC 4568 smoothly have a gap in the velocity axis. If two galaxies are “apparently” in contact with the celestial sphere and not interacting physically, the PVD should have a gap in the velocity axis. Figure 2 illustrates, however, that molecular gas in NGC 4567 and NGC 4568 smoothly have a gap in the velocity axis. If two galaxies are “apparently” in contact with the celestial sphere and not interacting physically, the PVD should have a gap in the velocity axis. Figure 2 illustrates, however, that molecular gas in NGC 4567 and NGC 4568 smoothly have a gap in the velocity axis.

In order to reveal the structure and the distribution of the molecular collision front, we integrate the flux over the velocity from 2330 to 2380 km s\(^{-1}\), where large velocity width is seen.
in Figure 2. Figure 3 shows that a long filamentary structure lies adjacent to the largest star-forming domain in the overlapping region. The filamentary structure matches a dark lane traced by the R-band image that is located between two progenitor galaxies and does not trace the spiral arms of both galaxies. The filamentary structure contains a number of local peaks, suggesting that the molecular collision front is made with an ensemble of molecular clouds. The size of the filament is 1800 pc × 350 pc (an aspect ratio of 5), and the mass is (2.24 ± 0.07) × 10^6 M☉ assuming the Galactic CO-H2 conversion factor of 1.8 × 10^20 K (km s⁻¹)⁻¹ (Dame et al. 2001). Note that the size and mass of the filament are a lower limit because about half of the CO flux is missing, as described above.

We average the spectra within the filament cloud (1800 pc × 350 pc) and fit it with the Gaussian function. The FWHM of the filament cloud is 39.5 ± 3.2 km s⁻¹. Therefore, the line-of-sight velocity dispersion σ is 16.8 ± 1.4 km s⁻¹. Regarding σ as the averaged squared velocity dispersion ⟨σ²⟩/2, we can calculate the virial mass per unit length based on Fiege & Pudritz (2000):

\[ m_{\text{vir}}/l = \frac{2\langle \sigma^2 \rangle}{G}, \]  

where G is the gravitational constant. We have \( m_{\text{vir}}/l \) of (1.3 ± 0.01) × 10⁶ M☉ pc⁻¹. Molecular gas mass per unit length, \( m_{\text{CO}}/l \), is 2.24 × 10⁷ M☉/1800 pc = 1.2 × 10¹⁶ M☉ pc⁻¹. Thus, the filament is currently gravitationally unbound.

4. Discussion and Conclusion

In order to figure out the physical conditions of the molecular clouds in the filament, we identify the molecular clouds using the CLUMPFIND software (Williams et al. 1995). With this spatial and velocity resolution data, a total of 215 clouds are resolved from the cube data, and four of them are found in the filamentary structure. The locations and physical properties of the four clouds embedded in the filament are illustrated in Figure 4 and Table 1, respectively. The four clouds have a deconvolved radius of ~30 pc and a luminosity mass of an order of 10⁶ M☉. The radius is comparable to the typical values for giant molecular clouds (GMCs; ~10⁷ M☉, 10–100 pc; Sanders et al. 1985; Koda et al. 2009), while the mass is between that of GMCs and giant molecular associations (GMAs; ~10⁴ M☉, >100 pc) in nearby galaxies (Tosaki et al. 2007; Donovan Meyer et al. 2013). We also derive the average deconvolved radius and luminosity mass for 211 molecular clouds located outside of the filament and find an average radius of 31.2 ± 29.1 pc and mass of (9.57 ± 0.03) × 10⁶ M☉, respectively. The molecular clouds in NGC 4567/4568 have higher molecular gas mass for their size (Bolatto et al. 2008), and the four molecular clouds inside the filament have the same deconvolved radius and slightly smaller luminosity mass compared with other clouds in NGC 4567/4568.

We calculate the virial mass \( M_{\text{vir}} \) assuming that the clouds are a spherical shape with truncated \( \rho \propto r^{-2} \) density profiles (MacLaren et al. 1988) and virial parameter \( \alpha_{\text{vir}} \) (Bertoldi & McKee 1992) for the clouds:

\[ M_{\text{vir}} = \frac{1040\sigma^2 R}{G}, \]  

\[ \alpha_{\text{vir}} = \frac{5\sigma^2 R}{GM}, \]

where \( R \) and \( M \) are the deconvolved radius and luminosity mass of the molecular cloud, respectively. The result shows that averaged \( \alpha_{\text{vir}} \) for all molecular clouds in NGC 4567/4568 is 0.27, which is significantly smaller than that of GMCs in nearby galaxies (Rosolowsky 2007; Wong et al. 2011), and almost all clouds (206/215) are gravitationally bound (\( \alpha_{\text{vir}} < 1 \)), including the four gas clouds in the filament. The low virial parameter is due to large luminosity mass for the cloud size. The results suggest that a galaxy collision contributes to the formation of heavier gas clouds.

We derive a free-fall time for the gas clouds in the filament by

\[ t_{\text{ff}} = \left( \frac{R^3}{GM} \right)^{1/2}. \]

We find all four molecular clouds embedded in the filament have the free-fall time of 10⁶ years, which is much shorter than
the timescale for a galaxy merger event. Hence, they will create an extended star-forming region.

How was the filament in the overlapping region made? These physical properties of the filament at the collision front obtained from our observations are consistent with the numerical simulation by Saitoh et al. (2009). They showed that a long filamentary gas structure (a giant filament) emerges during the first encounter due to shock compression. Although the mass of the filament that we found is two orders of magnitude smaller than that of the numerical simulation, an aspect ratio of their long filamentary gas structure is 5, which is comparable to that of the observed molecular filament in NGC 4567/4568. The correspondence of the molecular filamentary structure with the dark lane implies that the filament is denser than the surrounding molecular gas as expected from the simulations. Slow shock (∼50 km s\(^{-1}\)) traced by a CH\(_3\)OH maser is observed in the other interacting galaxies, VV 114, that is thought to be mid-stage merging (Saito et al. 2017). Thus, shock can occur during the galaxy interaction. These facts suggest that the molecular filament in NGC 4567/4568 was induced by shock.

We discuss the future of the shock-induced molecular filament in the overlapping region in NGC 4567/4568 by comparing it with the simulation. As shown in Figure 4, no star formation signature is seen in the filament. This could be explained by two possibilities, as summarized by Tanaka (2018). One is that a collision of progenitor disks inhibits star formation activity. A collision of clouds may stabilize them due to increased turbulent pressure (e.g., Johnston et al. 2014). Dobbs et al. (2014) showed that the velocity dispersion of a cloud becomes larger through a cloud–cloud collision event, leading to an increase of the virial parameter of the cloud. Recent observation also shows that a higher volume density is required to form stars in a high turbulent pressure environment (Rathborne et al. 2014). These results indicate that even if dense gas is formed by cloud collision, star formation may not occur as seen in the Galactic Center. The other possibility is that the filament is at an early phase of collision-triggered star formation, in which the conditions of star formation are just fulfilled. Saitoh et al. (2011), who described the evolution of the giant filament in the simulation, demonstrated that the giant filament becomes fragmented into smaller clumps. The stars that have been produced from these small clumps will merge and finally result in super star clusters. However, a collision of disks may ionize the pre-existing GMCs, and ionized gas soon returns to molecular gas if it is dense enough (Komugi et al. 2012). If ionization happens in the filament, star formation should be delayed. Based on this scenario, the molecular filament made by shock could be the progenitor of the off-center starburst and super star clusters in interacting galaxies.

Finally, we discuss where star formation takes place if the filament would form stars as simulated by Saitoh et al. (2011). The existence of gravitationally bound molecular gas clouds in the filament suggests that the filament would already be fragmented and starbursts would occur almost coincidentally in each cloud with a timescale of 10\(^6\) years, which is shorter than that in the simulations. On the other hand, some part of long-thin filaments in the Antennae Galaxies reported by Whitmore et al. (2014) is already star-forming, and the others are not. If the long-thin filaments in the Antennae Galaxies have the same origin as the filament in NGC 4567/4568, which is the collision of molecular disks, this fact implies that star formation in the filament might not happen simultaneously. As the length of the filament in NGC 4567/4568 is a half of that of the Antennae Galaxies, a shorter time-lag of star formation within the filament in NGC 4567/4568 is expected, meaning that clouds in the filament would have same physical properties. The likelihood of these possibilities, including whether star formation will occur in the filament, could be clarified by investigations with our dense gas tracers and higher resolution data (H. Kaneko et al. 2018, in preparation).

This paper makes use of the following ALMA data: ADS/JAO.ALMA\#2012.1.00759.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada) and NSC and ASIAA (Taiwan), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. Data analysis was in part carried out on the open use data analysis computer system at the Astronomy Data Center, ADC, of the National Astronomical Observatory of Japan.

Facility: ALMA.

**ORCID iDs**

Hiroyuki Kaneko (金子紘之) @ https://orcid.org/0000-0002-2699-4862

Takayuki R. Saitoh (齋藤貴之) @ https://orcid.org/0000-0001-8226-4592

**References**

Bertoldi, F., & McKee, C. F. 1992, ApJ, 395, 140

Bolatto, A. D., Leroy, A. K., Rosolowsky, E., et al. 2008, ApJ, 686, 948

Bushouse, H. A. 1986, AJ, 91, 255

Clements, D. L., Sutherland, W. J., McMahon, R. G., & Saunders, W. 1996, MNRAS, 279, 477

Dame, T. M., Hartmann, D., & Thaddeus, P. 2001, ApJ, 547, 792

Dobbs, C. L., Burkert, A., & Pringle, J. E. 2014, MNRAS, 413, 2935

Donovan Meyer, J., Koda, J., Momose, R., et al. 2013, ApJ, 772, 107

Fiege, J. D., & Pudritz, R. E. 2000, MNRAS, 311, 85

**Table 1**

| R.A. (J2000.0) | decl. (J2000.0) | Radius* (pc) | Systemic Velocity (km s\(^{-1}\)) | Velocity Dispersion* (km s\(^{-1}\)) | Luminosity Mass (10\(^4\) M\(_\odot\)) | Virial Mass (10\(^4\) M\(_\odot\)) | Virial Parameter | Free-fall Time (10\(^5\) years) |
|----------------|----------------|--------------|------------------------------------|--------------------------------------|--------------------------------------|-----------------------------------|-----------------|------------------------------|
| 12\(^h\)36\(^m\)35\(^s\)06 | 11\(^°\)15\('\)15\(″\)49 | 38.6 | 2365 | 3.9 | 320 | 62.1 | 0.22 | 2.3 |
| 12\(^h\)36\(^m\)35\(^s\)127 | 11\(^°\)15\('\)21\(″\)75 | 31.7 | 2370 | 1.1 | 122 | 3.6 | 0.03 | 2.7 |
| 12\(^h\)36\(^m\)35\(^s\)161 | 11\(^°\)15\('\)26\(″\)12 | 26.5 | 2375 | 5.7 | 407 | 88.2 | 0.24 | 1.1 |
| 12\(^h\)36\(^m\)35\(^s\)179 | 11\(^°\)15\('\)29\(″\)49 | 26.4 | 2380 | 2.5 | 87 | 17.6 | 0.23 | 2.5 |

Note.

* Radius and velocity dispersion are deconvolved values.
