ALMA VIEW OF G0.253+0.016: CAN CLOUD–CLOUD COLLISION FORM THE CLOUD?

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ABSTRACT

We present the results of the sulfur monoxide, SO, line emission observations of G0.253+0.016 with the Atacama Large Millimeter/Submillimeter Array at an angular resolution of 1.7″. The dense and massive molecular cloud of G0.253+0.016 is highly sub-structured, yet it shows no obvious signs of cluster formation. We found three outstanding features of the cloud from the SO emission, namely, shell structure with a radius of 1.3 pc, large velocity gradients of 20 km s−1 pc−1 with the cloud, and cores with large velocity dispersions (30–40 km s−1) around the shell structure. We suggest that these large-velocity dispersion cores will form high-mass stars in the future. In an attempt to explore the formation scenario of the dense cloud, we compared our results with numerical simulations; therefore, we propose that G0.253+0.016 may have formed due to a cloud–cloud collision process.

Key words: ISM: kinematics and dynamics – ISM: molecules – ISM: structure

Online-only material: color figures

1. INTRODUCTION

Most stars, particularly high-mass stars (> 8 M⊙), form in stellar clusters (Lada & Lada 2003). Stellar clusters form in dense and massive molecular clumps (size ∼ 1 pc, mass ∼ 100–1000 M⊙, density ∼ 104–105 cm−3; Ridge et al. 2003; Lada & Lada 2003; Higuchi et al. 2009, 2010, 2013). Dense gas in the cloud-forming clumps are significantly dispersed by the feedback from newly formed stars, thus blurring our understanding of cluster formation. To explore the initial conditions and details of cluster formation, it is necessary to study molecular clouds in the early stages of cluster formation.

One of the unresolved issues of cluster formation is how dense clouds evolve into the compact and massive stellar clusters, such as the “Arches” cluster (Lis & Menten 1998). The formation mechanism of such a super star cluster is mysterious because they are expected to form in massive and small clouds of 1 pc scale. Therefore, without an external triggering process, it may be impossible to form a super star cluster. In recent literature, cloud–cloud collisions are argued to be responsible for super star cluster formation (Furukawa et al. 2009; Fukui et al. 2009; Ohama et al. 2010). Furukawa et al. (2009) suggested that the young cluster Westerlund 2 likely formed by a cloud–cloud collision mechanism. Westerlund 2 is a remarkable galactic super star cluster, containing more than 10 massive stars with a total stellar mass of 4500 M⊙ in a small volume of only 1 pc in radius. The age of Westerlund 2 is suggested to be a few Myr (Ascenso et al. 2007; Furukawa et al. 2009; Rauw et al. 2007). G0.253+0.016 (hereafter G0.25) is very massive (∼ 2 × 105 M⊙, radius of 2.8 pc; Longmore et al. 2012) and dense (∼ 3 × 104 cm−3; Kauffmann et al. 2013), with a low dust temperature of 23 K (Rodríguez & Zapata 2013) and no obvious signs of cluster formation. G0.25 forms part of a 100 pc circumnuclear ring of clouds (Molinari et al. 2011) at 8.5 kpc distance (Longmore et al. 2012). G0.25 presents an interesting site for the study of the initial condition of super star cluster formation because it is more massive and dense than the Orion A cloud, but hardly forms any stars (Lis et al. 1994). The infrared luminosity of the entire cloud is 3 × 105 L⊙, suggesting the presence of at least five embedded stars at evolutionary stages earlier than B0 (Lis et al. 2001). Rodríguez & Zapata (2013) also suggested that there are no O stars associated with the cloud. Recently, Kauffmann et al. (2013) presented N2H+ results arguing that G0.25 is currently far from forming high-mass stars and clusters.

In this paper, we present a 1″7 resolution image of SO(v = 0 3(2)−2(1)) line emission from the Atacama Large Millimeter/Submillimeter Array (ALMA) Cycle 0 observations. SO molecular line emissions are known to trace relatively dense and active clouds in a region (Bachiller et al. 2001; Aladro et al. 2013; Hacar et al. 2013; Codella et al. 2014). We investigated the spatial distributions and velocity structures with high-resolution observations based on the ALMA archive data of G0.25 obtained with an extended configuration. The mosaic of the molecular line emission across this cloud were obtained at 90 GHz. We speculate that the G0.25 cloud may represent the precursor to a super star cluster.

2. OBSERVATIONS

G0.25 was observed with ALMA (Hills et al. 2010) during Early Science Cycle 0 with extended configuration, using the band 3 receivers. The array was in a configuration with projected baseline lengths between ∼ 36.1 and ∼ 452.8 m, sensitive to maximum angular scales of 9′.1 and providing a synthesized beam of 2′′30 × 1′′53. The field of view was ∼ 65′× 65′. A total of six data sets were collected, using 24 antennas of 12 m diameter and accounting for 4 hr of total integration time on target. Weather conditions were good and stable; the system temperature varied from 50 to 60 K.

The correlator was set up to four spectral windows in dual polarization mode, centered at 89.10000 GHz, 87.20000 GHz, 99.10000 GHz, and 101.10000 GHz. For each of the spectral windows, the effective bandwidth used was 1875 MHz, corresponding to velocity resolutions of 3.286, 3.357, 2.954, and 2.896 km s−1, respectively, after Hanning smoothing.
Figure 1. Top: image of the WISE 3.4 μm, 4.6 μm, and 22 μm composite color image. Bottom: integrated intensity map of the SO(v = 0 3(2)–2(1)) emission in a range of −60 to 110 km s⁻¹ (color and contours). The contours with the intervals of the 30σ levels start from the 30σ levels, where the 1σ noise level is 3 mJy beam⁻¹. The H₂O maser reported by Lis et al. (1994) is marked. The black line shows a 2 pc scale. The filled circle in the bottom left corner shows the effective resolution of 1.7″.

(A color version of this figure is available in the online journal.)

In this work, we present results from the observations in the SO(3(2)–2(1)): 99.29987 GHz emission line. The ALMA calibration includes simultaneous observations of the 183 GHz water line with water vapor radiometers that measure the water column in the antenna beam, later used to reduce the atmospheric phase noise. Amplitude calibration was done using Neptune, and quasars J1717−337 and J2225−049 and NRAO 530 were used to calibrate the bandpass and the
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Figure 2. Left: integrated intensity map of the SO($v = 0\ 3(2)\rightarrow2(1)$) emission (contours) superposed on the first moment map (color). Right: integrated intensity map of the SO($v = 0\ 3(2)\rightarrow2(1)$) emission (contours) superposed on the second moment map (color). The contours with the intervals of the 30σ levels start from the 30σ levels, where the 1σ noise level is 3 mJy beam$^{-1}$. The black line shows a 2 pc scale. The filled circle in the bottom left corner in each panel shows the effective resolution of 1″.

(A color version of this figure is available in the online journal.)

3. RESULTS

3.1. Spatial Distributions of the SO Emission

Figure 1 shows the integrated intensity map of the SO($v = 0\ 3(2)\rightarrow2(1)$) emission. There is a clear shell-like structure with a radius of ∼1.3 pc in the integrated intensity map of SO. We made the map using only an interferometric data set, which implies that we are only seeing features of the shell-like structure within the size of 9″. All components above this scale were resolved out. Comparing our SO map with the dust continuum map traced by SCUBA 450 μm in Longmore et al. (2012), we found that the strong dust continuum traces the shell-like structure within the cloud. From the comparisons, we interpreted that the shell structure traced by SO emission is not an artifact of the interferometric observations. We defined the SO emission enclosed in the 30σ contours of the integrated intensity map as SO cores. We named these cores, which are effectively larger than the spatial resolution of the observations, as cores $A$–$N$ (see Figure 1). SO emission has been detected in some shocked regions, e.g., outflow shocked region in L 1157 (Bachiller et al. 2001), tracing the cavity opened by the jet in NGC 1333 (Codella et al. 2014), and NGC 1068 (Aladro et al. 2013), implying that observed shell structure in G0.25 may have been due to shock-related activity in the region. We also found that there are hub-filament structures and cores (cores $C$–$I$, and $N$), which are connected to the shell-like structure. Comparing Figure 1 with the WISE image of G0.25, we see that the SO emissions trace the network of parsec-long filaments seen in dust extinction. Because of the high resolution offered by the ALMA telescope, the image of the network of parsec-long filaments has been clarified.

The SO abundance is thought to be enhanced in a high-temperature environment and/or in the late stages of molecular cloud evolution. These characteristics are mainly due to the formation of SO via neutral–neutral reactions such as

$$S + OH \rightarrow SO + H.$$  (1)

Neutral–neutral reactions are generally slower than ion–molecule reactions and tend to have activation energies, that must be overcome during the reactions. The effects of neutral–neutral reactions on SO formation were reviewed previously in a paper by Takano et al. (1995). In the above point of view, the regions with enhanced SO intensity in the obtained ALMA image can be in a relatively dense, late stage of molecular cloud evolution and/or high temperature. The non-detection of $N_2H^+$ (Kauffmann et al. 2013) around the cores $C$–$H$ and $J$, which are SO peak regions studied by Kauffmann and collaborator, could be due to the relatively higher temperatures of the shocked region. The dense regions can accelerate the formation of SO via slow neutral–neutral reactions by increasing the collision rate between the reactants.
3.2. Velocity Structures of the Cores Traced by SO Emission

3.2.1. First and Second Moment Maps

In order to investigate the detailed velocity structures of the cloud, unveil the presence or absence of velocity gradients, identify cores with large velocity dispersion ($\sigma_v$, $\sigma_v$ is the one-dimensional velocity dispersion), we produced first and second moment maps (Figure 2). From the first moment image, cores A–F and I have velocities of 0–40 km s$^{-1}$, and cores K–N and H of the cloud have 40–100 km s$^{-1}$. The overall velocity structure of the cloud has a velocity difference of $\sim$100 km s$^{-1}$. We estimated the velocity gradient ($\sigma_{\text{grad}}$, $v_{\text{diff}}/2R$, where $v_{\text{diff}}$ is the velocity difference of $\sim$100 km s$^{-1}$ and $R$ is the radius of the cloud, to be $\sim$20 km s$^{-1}$ pc$^{-1}$ within the entire cloud.

Furthermore, from the second moment image, we found the cores associated with SO large velocity dispersions ($\sigma_v \sim 30–40$ km s$^{-1}$) along the shell-like structure, which may indicate the interactions between molecular gas and external effects. Within the filament, cores C, H, I, K, and N have large velocity dispersions. The velocity dispersions observed along the shell structures are most likely due to external shock, while the dispersion observed within the filament could be associated with very early phases of star formation, considering the presence of $\sim$22 GHz H$_2$O masers (Kauffmann et al. 2013). This is the first time that such large velocity dispersions have been observed in G0.25. The mechanisms of enhancement of large velocity dispersions are unclear. However, there is no evidence of the existence of the H II region and external effects (e.g., stellar wind, supernova remnant).

3.2.2. Position–Velocity Diagram

In order to investigate the velocity structures of the SO cores in detail, we made two position–velocity ($P$–$V$) diagrams (see Figure 3). Figure 3(a) shows integrated intensity SO emission as a function of both right ascension (R.A.) and velocity, and Figure 3(b) as a function of declination and velocity, i.e., the data cube collapsed along each spatial axis. Figure 3(a) shows a “hole” around $V_{\text{LSR}} \sim 30$ km s$^{-1}$, an indication of the observed...
shell-like structures. In Figure 3(b), we obtained bulk linear velocity gradients with multiple components. These could be multiple components with different velocities on a rigid-like rotation. We also made P–V diagrams for the G0.25 cloud with different position angles (see Figure 4). The axis of the slice covers the entire SO shell structure. From these results, we found that there are multiple components with different velocities at different position angles.

4. DISCUSSION

4.1. Kinematic Structures of the Cloud

We found that the G0.25 cloud has velocity gradients in the first moment maps as shown in Figure 2. As discussed in the Section 3.2, we found the following kinematic signatures: (1) here exists distinct velocity gradients, (2) they have multiple velocity components on a rigid-like rotation, and (3) large velocity dispersion cores are distributed mainly around the shell structure, with a few such cores within the filaments. We regard the above kinematic condition as being one of the key structures in massive cloud formation. We examined the energy balance of the cloud using the equilibrium virial theorem (e.g., Goodman et al. 1993; Stahler & Palla 2005):

\[ 2K + 2U + W + B = 0, \]

where \( K \) is the kinetic energy; \( U \) is the energy contained in random, thermal motion; \( W \) is the gravitational potential energy; and \( B \) is the energy of magnetic field. Here, we ignore the effect of the magnetic field. From the description of Stahler & Palla (2005), we form the ratios \( K/W \) and \( U/W \) as below:

\[ \frac{K}{W} \sim 0.5 \left( \frac{\Delta V}{4 \text{ km s}^{-1}} \right)^2 \left( \frac{M}{10^5 M_{\odot}} \right)^{-1} \left( \frac{R}{25 \text{ pc}} \right), \]

\[ = 0.1 \left( \frac{\sigma_v}{4 \text{ km s}^{-1}} \right)^2 \left( \frac{M}{2 \times 10^5 M_{\odot}} \right)^{-1} \left( \frac{R}{2.8 \text{ pc}} \right), \]

where \( \Delta V \) is the velocity width in FWHM (\( \Delta V = \sqrt{8 \ln 2} \sigma_v \)), \( M \) is the mass, and \( R \) is the radius of the cloud. We used mean value of the velocity dispersion of SO (\( \sigma_v \sim 4 \text{ km s}^{-1} \)) in the second moment map:

\[ \frac{U}{W} \sim 3 \times 10^{-3} \left( \frac{M}{10^5 M_{\odot}} \right)^{-1} \left( \frac{R}{25 \text{ pc}} \right) \left( \frac{T}{15 \text{ K}} \right), \]

\[ = 2 \times 10^{-2} \left( \frac{M}{2 \times 10^5 M_{\odot}} \right)^{-1} \left( \frac{R}{2.8 \text{ pc}} \right) \left( \frac{T}{20 \text{ K}} \right), \]

where \( T \) is the representative gas temperature of the cloud. From our estimation, the cloud tends to be gravitationally stable.

Meanwhile, the velocity gradients are seen in the entire G0.25 cloud. We compared our result with the previous studies of velocity gradients of clouds in Larson (1983) and Goodman et al. (1993), which shows the plot of \( \sigma_{\text{grad}} \) as a function of the cloud size:

\[ \sigma_{\text{grad}} = 0.33 \left( \frac{R}{2.8 \text{ pc}} \right)^{-0.44 \pm 0.2} \text{ km s}^{-1} \text{ pc}^{-1}, \]

where \( \sigma_{\text{grad}} \) is the velocity gradient of the cloud and \( R \) is the radius of the cloud. If we apply the cloud size of 2.8 pc, the velocity gradient becomes 0.33 km s\(^{-1}\) pc\(^{-1}\), which is an order of magnitude smaller than our result of 20 km s\(^{-1}\) pc\(^{-1}\). Such a large velocity gradient in the cloud is strange compared with the previous studies of the star-forming regions. These observational results imply that these velocity structures are related to the initial conditions in the cloud and must be preserved during the ages (several \( 10^5 \) yr; Kauffmann et al. 2013).

4.2. Comparison with the Simulation

The filamentary structures and cores of SO in the G0.25 cloud are very similar to results of cloud–cloud collision
simulations. Habe & Ohta (1992) simulated head-on collision between non-identical clouds with supersonic relative velocities in order to investigate star formation triggered by cloud–cloud collisions. They assumed that the mass ratio of both clouds is 1:4 and the radius ratio is 1:2. They considered internal random motions of clouds as the effective sound speeds. The clouds collided with each other with Mach numbers of the relative speeds, \(5 \sim 10\). Since their simulation was carried out assuming the isothermal equation of state, we can change the physical parameters of the small cloud into the radius of \(\sim 1.5\) pc and mass of \(\sim 0.5 \times 10^5 M_\odot\), and the larger one into the radius of \(\sim 3\) pc and mass of \(\sim 2 \times 10^5 M_\odot\). Their relative speeds are \(\sim 30–60\) km s\(^{-1}\), which are consistent with our result. They found that a gravitational instability is triggered by a non-identical cloud–cloud collision. They showed that the large cloud is disrupted and shell structures are formed by the bow shock induced by the collision with the small cloud and that the small cloud is compressed by the shock induced by the collision with the large cloud and its gravitational collapse is triggered. Anathpindika (2010) also discussed the stability of the bow shock resulting from their simulation of head-on collision between clouds of different sizes. Three-dimensional simulations of similar collisions between non-identical clouds were performed by Takahira et al. (2014) submitted that explored formation of filamentary structures and dense cores in the collision between clouds of different masses under varying collision velocities. They also show the formation of the bow shock at the collision interface, the inclusion of turbulence producing a jagged shell of shocked gas. This fragmented into multiple dense cores, which rapidly accreted while in the shocked gas to form objects that could be the precursors to massive stars. These features are very similar to our observation. Inoue & Fukui (2013) demonstrate that massive and gravitationally unstable molecular cloud cores are formed behind the strong shock waves induced by cloud–cloud collision. The conclusions drawn here may also be relevant to the shells driven by powerful winds from young super star clusters or expanding supernovae shells. However, there is no evidence of such external effects in the G0.25 cloud; we suppose that cloud–cloud collision is a reasonable mechanism to trigger massive cloud formation for G0.25. Figure 5 shows the schematic image of the cloud–cloud collision for G0.25.

Previous studies also proposed the cloud–cloud collision mechanism for the G0.25 cloud in the discussion section of Kauffmann et al. (2013). Lis & Menten (1998) and Lis et al. (2001) take the existence of widespread SO emission as evidence for an ongoing cloud–cloud collision. The cloud–cloud collision mechanism is previously considered as an efficient mechanism to trigger star formation, but it also leads to the destruction of cluster-forming systems rather than gravitational collapse. However, Furukawa et al. (2009) reported super star cluster formation triggered by the cloud–cloud collision mechanism. From the recent results, cloud–cloud collision is a reasonable mechanism to form the initial condition of the super star cluster, e.g., infrared dark cloud.

4.3. Implication: Existence of Large-\(\sigma_v\) Cores

Ikeda et al. (2007) carried out the \(^{13}\)CO\(^\ast\)(1–0) core survey, covering the entire Orion A molecular cloud using the Nobeyama 45 m radio telescope. They found three cores toward the M42 H\(\alpha\) region with velocity dispersions \(\sigma_v\) significantly larger than those of the other cores, suggesting that the energy input from the H\(\alpha\) region increases the velocity dispersion. The large-\(\sigma_v\) cores have the potential to form the most massive stars because the mass infall rate is proportional to the third power of the velocity width \((M = 0.975 c_{\text{eff}}^3 / G);\) from McKee & Tan (2003). From the second moment map of SO, we found that the areas of large velocity dispersion \(\sigma_v \sim 30–40\) km s\(^{-1}\) are distributed along the shell-like structure. Liu et al. (2013) also found these cores in the Sgr A region. From the above results, we consider that these regions possibly contain large-\(\sigma_v\) cores, which will form high-mass stars. SO emission has been detected in the active and shocked region (e.g., Bachiller et al. 2001; Aladro et al. 2013; Codella et al. 2014). We interpreted that Kauffmann et al. (2013) proposed that the G0.25 cloud has a lack of dense cores, which will form stars immediately. These cores will be detected by dense gas tracers (e.g., \(^{13}\)CO\(^\ast\), \(N_2H^\ast\), \(10^5–6\) cm\(^{-2}\); Kauffmann et al. 2013). However, an SO molecule is considered to trace more active cores than \(N_2H^\ast\) cores. It will take time to form stars because the SO cores will be gravitationally bound due to the turbulence decay. Thus, we understand that the G0.25 cloud is in the very early stage of star formation, triggered by the cloud–cloud collision.
5. CONCLUSIONS

We present the results of the sulfur monoxide, SO, line emission observations of G0.25 with ALMA, at an angular resolution of 1''.7. Our results and conclusions are summarized as follows.

1. We presented the SO map with a size of \( \sim 3' \times 1.5' \) for the G0.25 cloud. We identified detailed filamentary structures and cores within the cloud with high-resolution observations.

2. We discovered the shell structure with a radius of 1.3 pc with the SO emission. SO emission has been detected in some shocked regions, e.g., outflow shocked region in L 1157 (Bachiller et al. 2001), tracing the cavity opened by the jet in NGC 1333 (Codella et al. 2014), and NGC 1068 (Aladro et al. 2013), implying that the observed shell structure in G0.25 may have been due to shock-related activity in the region.

3. We found large velocity gradients of \( \sim 20 \text{ km s}^{-1} \text{ pc}^{-1} \) within the cloud, and cores with large velocity dispersions (\( \sim 30-40 \text{ km s}^{-1} \)) around the shell structure. We suggest that these high-velocity-dispersion cores will form high-mass stars in the future.

4. We estimated the virial ratios, taking into account the contribution of rotation and found that the G0.25 cloud is likely to be in a gravitationally bound condition. However, large velocity gradients in the G0.25 cloud are strange compared with the previous studies of the star-forming regions. In order to explain the physical conditions of G0.25, we compared our results with numerical simulations; we propose that G0.25 may have formed due to a cloud–cloud collision process.

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