DISCOVERY OF INFALLING MOTION WITH ROTATION OF THE CLUSTER-FORMING CLUMP S235AB AND ITS IMPLICATION TO THE CLUMP STRUCTURES

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ABSTRACT

We report the discovery of infalling motion with the rotation of S235AB, a massive cluster-forming clump (∼1 × 10²° M☉) in the S235 region. Our C18O observations with the 45 m telescope at the Nobeyama Radio Observatory have revealed an elliptical shape of the clump. A position–velocity diagram taken along its major axis exhibits two well-defined peaks symmetrically located, with respect to the clump center. This is similar to that found for a dynamically infalling envelope with rotation around a single protostar, modeled by N. Ohashi et al., indicating that the cluster-forming clump is also collapsing by the self-gravity toward the clump center. With analogue to Ohashi et al.’s model, we made a simple model of an infalling, rotating clump to fit the observed data. Based on the inferred model parameters, as well as results of earlier observations and simulations in the literature, we discuss the structures of the clump such as the relation among the global mass infall rate (∼1 × 10⁻⁵ M☉ yr⁻¹), formation of a compact core (with a mass and size of ∼4 M☉ and ∼0.1 pc) at the center, and a massive star (∼11 M☉) forming in the core.

Key words: ISM: clouds – ISM: individual (S235) – ISM: kinematics and dynamics – ISM: molecules – stars: formation

1. INTRODUCTION

Dynamics of cluster-forming clumps is of particular interest because most stars are formed in clusters (e.g., Lada & Lada 2003). The velocity fields of massive cluster-forming clumps (∼1000 M☉), traced by some high-density tracers (e.g., H13CO+, C18O, etc.), is often complex, exhibiting two or more velocity components. These components are sometimes interpreted as evidence of clump–clump collisions (e.g., Higuchi et al. 2009; Torii et al. 2011), collisions of filaments (e.g., Dobashi et al. 2014; Nakamura et al. 2014; Matsumoto et al. 2015), or clumps blown by expanding compact H II regions (e.g., Shimoikura et al. 2015). It is also possible that the velocity components are due to vibrations of the clumps, as suggested for the small starless core B68 (Lada et al. 2003). Although all of these can be reasonable interpretations for some particular cases, we should also consider the most likely possibility that they are tracing the internal motions of the clumps dominated by self-gravity, i.e., the dynamically infalling motions with rotation.

In an early stage of cluster formation, when the dynamics of the natal clump is not yet strongly influenced by the internal cluster, we would expect that the motion of the clump must follow simple kinetic laws dominated by the self-gravity, with increasing infall and rotation velocities toward the center of the clump. This is similar to the case of single protostars (e.g., Ohishi et al. 1997; Momose et al. 1998; Bernard et al. 1999), indicating that the cluster-forming clumps should also be collapsing toward the clump center by the self-gravity, like in the case of single protostars. In the past, infalling motions of cluster-forming clumps have been discovered by some authors (e.g., Peretto et al. 2006, 2007;
Barnes et al. 2010; Reiter et al. 2011), but their data would be more naturally understood if we considered the rotation in addition to the infall, as we found in this paper.

The clump studied here is one of the most typical cases showing infalling motion with rotation. It is cataloged as No. 4423 (Dobashi 2011) or TGU H1192P1 (Dobashi et al. 2005) in the catalogs of dark clouds, and two compact H II regions called S235A and S235B (e.g., Felli et al. 2004; Klein et al. 2005; Saito et al. 2007) are located in this clump (see Figure 1). Throughout this paper, we will call this clump S235AB. An embedded star cluster has been identified (e.g., Camargo et al. 2011; Dewangan & Anandarao 2011; Chavarría et al. 2014), and the most massive member of the cluster, named S235AB-MIR (Felli et al. 2006), is located at the clump center (~11 M\(_{\odot}\); Dewangan & Anandarao 2011). Several signposts of early stellar evolution, such as a molecular outflow (e.g., Nakano & Yoshida 1986; Felli et al. 2004) and a fast jet traced by water maser emission (~50 km s\(^{-1}\), Burns et al. 2015), have also been found. S235AB should therefore be suited to detect and quantify the infalling motion with rotation. Estimates of the distance to the clump vary in the range of 1.6–2.5 kpc (e.g., Israel & Felli 1978; Burns et al. 2015), and we adopt a value of 1.8 kpc in this paper, following Evans & Blair (1981).

2. OBSERVATIONS

In order to carry out a statistical study of cluster-forming clumps found in a catalog of dense cores (Dobashi 2011; Dobashi et al. 2013), we made molecular line observations of several massive clumps, including S235AB, with the NRO 45 m telescope for 10 days in 2013 February. We observed the clumps in some molecular lines, including \(^{12}\)CO\((J = 1–0)\), \(^{13}\)CO\((J = 1–0)\), and \(^{18}\)O\((J = 1–0)\), with a Superconductor–Insulator–Superconductor (SIS) receiver named TZ (Asayama & Nakajima 2013). We used spectrometers called SAM45, which have 4096 channels and a frequency resolution of 7.6 kHz. We performed a standard on-the-fly mapping (Sawada et al. 2008) around the target clumps and convolved the data with a spherical function to resample them at the 7\(\prime\)5 grid along the equatorial coordinates.

More details of the observations will be given in a subsequent publication together with results of statistics of the observed clumps (T. Shimoikura et al. 2016, in preparation). In this paper, we will concentrate on the analyses of the velocity field of S235AB mainly using \(^{18}\)O data. The angular resolution and noise levels of the \(^{18}\)O data are 22\(\prime\) and \(\Delta T_{mb} \approx 0.3 \) K at a velocity resolution of 0.1 km s\(^{-1}\).

3. RESULTS

Figure 1(a) shows the \(^{18}\)O intensity distribution of S235AB integrated over the velocity range \(-20 < V_{LSR} < -14 \) km s\(^{-1}\). The clump has a well-defined single peak between the two small H II regions (S235A and S235B), and has an elliptical shape with an intense ridge elongating toward the north-east direction. A fainter outskirt extends to the south toward another small H II region, named S235C (see Figure 5(d) in Appendix A).

We should note that the region shown in Figure 1(a) has been observed by Higuchi et al. (2009, see their Figure 3). Their \(^{18}\)O map appears slightly different from ours, showing a double-peaked structure, while our map in Figure 1(a) shows a single peak between S235A and S235B. We believe that this is simply because of the different velocity ranges used for the integration. Though the velocity range used for the integration is not stated in their paper, our map would appear very similar to theirs if we adopted a narrower velocity range \((-18 < V_{LSR} < -15 \) km s\(^{-1}\)). Higuchi et al. (2009) argue that a clump–clump collision has induced cluster formation in the S235AB region, and they classified the clump as “Type C” (i.e., the later stage of cluster formation) based on the
morphology. In the S235AB region, however, many young stellar objects (YSOs) have been discovered by Dewangan & Anandarao (2011), and their results show that the source S235AB-MIR is a very young massive protostar that is not yet able to excite an H II region. The source is apparently located at the center of the clump, indicating that the clump is most likely to be the natal clump of the source. We therefore regard that the clump shown in Figure 1(a) is a distinct system not directly associated with the S235A or S235B H II regions, and that a new cluster formation has just initiated in this clump, following cluster formation in the two H II regions.

In Figure 2, we show an example of the $^{12}$CO, $^{13}$CO, and C$^{18}$O spectra observed around the peak position of the clump. While the optically thick $^{12}$CO spectrum consists of two or more velocity components, the optically much thinner C$^{18}$O and $^{13}$CO spectra apparently have a single component at $V_{\text{LSR}} \approx -16.7 \, \text{km s}^{-1}$, which should be the main component of the clump. In the following analyses, we will focus on this component and will briefly show the other minor velocity components detected mainly in $^{12}$CO in Appendix A.

To estimate the molecular mass of the clump, we first estimated the excitation temperature of the C$^{18}$O molecules from the peak brightness temperature of the $^{12}$CO emission line at each position in the mapped region as displayed in Figure 1(b), and we calculated the C$^{18}$O column density $N(\text{C}^{18}\text{O})$ in a standard way on the assumption of the Local Thermodynamic Equilibrium (e.g., see Section 3.2 of Shimoikura et al. 2013). We then converted $N(\text{C}^{18}\text{O})$ to the column density of the hydrogen molecules $N(\text{H}_2)$ using the empirical relation $N(\text{C}^{18}\text{O})/N(\text{H}_2) = 1.7 \times 10^{-7}$ (Frerking et al. 1982). The resulting $N(\text{H}_2)$ map is shown in Figure 3(a). We defined the surface area of the clump $S = (0.35 \, \text{pc})^2$ by the contour drawn at half of the peak $N(\text{H}_2)$ value ($1.4 \times 10^{23} \, \text{H}_2$ cm$^{-2}$), and we also defined the mean clump radius $R_0 = (0.34 \, \text{pc})$ as $R_0 = \sqrt{S/\pi}$. The clump mass $M$ contained in $S$ is estimated to be $680 \, M_\odot$. To measure the ellipticity of the clump $e_{\text{obs}}$, we fitted the $N(\text{H}_2)$ distribution with a two-dimensional elliptical Gaussian function, for which we found $e_{\text{obs}} = 0.58$. The two-dimensional Gaussian fit infers that the total mass of the clump, including periphery outside $S$, to be $1340 \, M_\odot$. We summarize these observed properties in Table 1, and will use them to model the clump in Section 4.

Concerning the velocity field, the clump exhibits a typical C$^{18}$O line width of $\Delta V = 1.8 \, \text{km s}^{-1}$ (FWHM). Peak radial velocities of the emission line stay around $V_{\text{LSR}} = -16.7 \, \text{km s}^{-1}$, which should represent the systemic velocity ($V_{\text{sys}}$) of the clump. It is notable that, with respect to the systemic velocity, the observed velocities of the emission line exhibit an interesting symmetry around the intensity peak position. The feature can be easily recognized in the position-velocity (PV) diagram shown in Figure 3(b) taken along the major axis of the clump. The figure shows a clear velocity gradient around the center of the clump with two well-defined peaks at the positions $\pm 0.35 (\approx 3.8 \times 10^4 \, \text{au})$ and at velocities $V_{\text{LSR}} \approx -17.2$ and $-16.2 \, \text{km s}^{-1}$ (separated by $\pm 0.5 \, \text{km s}^{-1}$ from $V_{\text{sys}}$), and they get close to $V_{\text{sys}}$ at the outer sides of the clump. Figure 3(c) displays another PV diagram measured along the minor axis of the clump, and we can see a slight velocity gradient.

We should note that the features of the PV diagrams, especially the one seen along the major axis, are very similar to what has been found for infalling envelopes with rotation around single protostars (e.g., Ohashi et al. 1997; Momose et al. 1998; Bernard et al. 1999). This indicates that the internal motion of the cluster-forming clump should follow a mechanism similar to that for the envelopes of single protostars in spite of the large difference in size and mass.

4. MODEL

To understand the velocity distributions observed in C$^{18}$O, we made a simple model of an infalling clump with rotation with analogy to the model proposed by Ohashi et al. (1997). Their model is for a thin disk around a single young low-mass star, and the motion of the disk is assumed to be entirely dominated by the central stellar mass, because the disk mass is much smaller. They therefore assume that $V_{\text{inf}}$, the infalling velocity, and $V_{\text{rot}}$, the rotational velocity, are $V_{\text{inf}} \propto r^{-0.5}$ and $V_{\text{rot}} \propto r^{-1}$, respectively, for conservations of total energy and angular momentum. They also assume that the density of the disk $\rho$ follows that of a free-falling disk ($\rho \propto r^{-1.5}$). Based on the simple model, they successfully accounted for the observed velocity field of a disk around IRAS 04368+2557 in LDN 1527.

In the case of the cluster-forming clump studied here, the velocity field of the clump should not be as simple as for the case of the low-mass star, because the mass of the system cannot be represented by a single particle at the center of the clump, but is distributed over a wide region in volume. In addition, in the inner region of the clump, there must be forces of clump-support, such as the turbulence and magnetic field, which are difficult to quantify at the moment. Moreover, the clump may not be treated as a disk, because it has apparently a certain thickness.

In this study, we therefore assume an ellipsoidal clump with an ellipticity of $e_0$ as illustrated in Figure 4, and assume that $\rho$, $V_{\text{inf}}$, and $V_{\text{rot}}$ of the clump can be approximated by the
Figure 3. Upper panels: distributions of the H$_2$ column density derived from the C$^{18}$O integrated intensity, observed position–velocity diagram measured at the cut 1–1$'$ along the x$_0$ axis, and that measured at the cut 2–2$'$ along the y$_0$ axis, are displayed in panels (a)–(c). The lowest contours and contour intervals are $1 \times 10^{21}$ H$_2$ cm$^{-2}$ in panel (a), and $5 \times 10^{21}$ H$_2$ cm$^{-2}$ (km s$^{-1}$)$^{-1}$ in the other panels. Middle panels: same as in the upper panels, but for the model best fitting the observed data. Contours are the same as in the upper panels. The center of the model clump is set to the peak position of the H$_2$ column density map in panel (a). A linear scale for 50,000 au is indicated in panel (d), and a common resolution for all of the position–velocity diagrams (22$''$ and 0.2 km s$^{-1}$) is shown in panel (f). Lower panels: observed (black lines) and model (red lines) spectra sampled at the center of the clump ($x_0 = 0''$), as well as at the positions $x_0 = \pm 22''$ along the cut 1–1$'$ corresponding to the two peaks in panels (b) and (e). The spectra are in units of the H$_2$ column density. The vertical broken lines denote the systemic velocity ($V_{lsr} = -16.7$ km s$^{-1}$).
Table 1
Observed Properties of the Clump

| Quantities                  | Values                | Comments                        |
|-----------------------------|-----------------------|---------------------------------|
| $S$ (pc$^2$)                | 0.35                  | Surface area defined at the half of the peak $N(H_2)$ value |
| $R_0$ (pc)                  | 0.34                  | Mean radius calculated as $\sqrt{S/\pi}$ |
| $M$ ($M_\odot$)            | 680                   | Mass contained in $S$. Total mass inferred from the Gaussian fit is $1340 M_\odot$ |
| $N(H_2)$ (H$_2$ cm$^{-2}$) | $1.4 \times 10^{23}$ | Peak H$_2$ column density |
| $V_{ex}$ (km s$^{-1}$)      | $-16.7$              | Systemic velocity |
| $\Delta V$ (km s$^{-1}$)   | 1.8                   | Typical line width of the C$^{18}$O emission line (FWHM) |
| $e_{obs}$                   | 0.58                  | Apparent ellipticity |
| $V_{rot}(R)/\sin \theta$ (km s$^{-1}$) | 0.5               | Apparent rotation velocity at $R = 6.5 \times 10^4$ au |

Note that Equations (1)–(3) are approximated by $\rho \propto r^{-\alpha}$, $V_{inf} \propto r^{-\beta}$, and $V_{rot} \propto r^{-\gamma}$ for large values of $r$ and $R$. To make the equations equivalent to those assumed by Ohashi et al. (1997), we assume $\alpha = 1.5$, $\beta = 0.5$, and $\gamma = 1$ in this paper.

In order to reproduce the observed C$^{18}$O spectra, we set a cube of $256^3$ pixels with a pixel size of 2000 au (corresponding to $\sim 1/20$ of the angular resolution of the observations), and calculated $\rho$, $V_{inf}$, and $V_{rot}$ at each pixel according to the equations, and then integrated the number of H$_2$ molecules as a function of velocity along the line of sight of the observers who view the clump at an angle of $\theta$, with respect to the rotation axis of the clump (see Figure 4). Resulting spectra are smoothed with a Gaussian beam with a width of $39600$ au (FWHM) and are resampled onto the $13500$ au grid, corresponding to the same beam size ($22''$) and grid ($7/5$) of the observations at the assumed distance ($1.8$ kpc). In the calculations, we made integrations along the line of sight up to $r = 2R_0$ from the center of the clump where $R_0$ is the observed clump radius mentioned earlier ($0.34$ pc $\approx 6.8 \times 10^4$ au), and we also imposed a velocity dispersion of $\Delta V = 1.8$ km s$^{-1}$ (FWHM) to the gas contained in each pixel.

In our model, there are seven parameters in total, i.e., $e_0$, $\theta$, and the five parameters ($\rho_0$, $V_{inf}^0$, $V_{rot}^0$, $R_0$, and $R_\star$) in Equations (1)–(3). It is noteworthy that we can set strong restrictions to some of the parameters from the observed data. First, there is a certain relation between $e_0$ and $\theta$ to reproduce the observed ellipticity $e_{obs}(=0.58)$. Second, $R_0$ in Equation (1) is rather independent on the other parameters and can be decided by comparing directly with the observed column density, for which we found $R_0 = 4.7 \times 10^4$ au. Third, $\rho_0$ (and thus $n_0$) can be decided by comparing with the observed peak $N(H_2)$ value ($=1.4 \times 10^{23}$ cm$^{-2}$). Finally, the quantity $V_{rot}(R_0)/\sin \theta$ gives an estimate for $V_{rot}^0$ in Equation (3) where $V_{rot}(R_0)$ is the observed rotation velocity at a large radius of $r = R_0$ on the outer edge of the clump. As seen in Figure 3(b), we found $V_{rot}/\sin \theta \approx 0.5$ km s$^{-1}$ for $R_0 = 6.5 \times 10^4$ au ($=0.06$).

Under these restrictions, we fitted the observed PV diagrams in Figure 3 by varying $e_0$, $V_{inf}^0$, and $R_\star$ to find a set of the parameters minimizing $\chi^2$. Parameters best fitting the data determined in this manner are summarized in Table 2 together with uncertainties at the 90% confidence levels. In Figures 3(e) and (f), we show the PV diagrams for the best model that can be directly compared with the observed PV diagrams in Figures 3(b) and (c). Spectra taken from the model and observations are also compared in Figures 3(g)–(i). As can be seen in the figure, the model reproduces the observed PV diagrams well, though the clump is not an ideal ellipsoid but has apparent distortion in some aspects. It should be important
to point out that the observed two well-defined peaks seen in Figure 3(b) and a slight velocity gradient seen in Figure 3(c) can be reproduced only when we assume the infalling motion of the clump, and cannot be reproduced by any sets of parameters with V_{inf} = 0, indicating that the clump is actually collapsing.

In addition to the analyses based on the C^{18}O data, the infalling motion of the clump can also be supported by the asymmetric shape of the optically thick 12CO emission line (Figure 2) exhibiting a higher blueshifted component compared to the redshifted component, which is a characteristic feature of collapsing cores (e.g., Zhou et al. 1993). The feature can be better recognized in PV diagrams of 12CO, shown in the upper panels of Figure 6 in Appendix B, measured along the same cuts as in Figure 3. As detailed in Appendix B, we further attempted to reproduce the PV diagrams of 12CO based on the model parameters summarized in Table 2, assuming a flat 12CO fractional abundance as well as a 3D distribution of the excitation temperature peaking at one of the small H II regions (S235A). Resulting PV diagrams are displayed in the lower panels of Figure 6. We found that the observed higher blueshifted 12CO emission both along the major and minor axes (indicated by arrows in the figure) can be reproduced only when we assume the infalling motion (V_{inf} ≠ 0) strongly supporting our conclusion, that the clump is collapsing.

We should note that the best values for the parameters R_d and R_c in Table 2 do not match each other, and R_d (∼4.7 × 10^4 au) is significantly larger than R_c (∼6.4 × 10^4 au) by an order of magnitude. The parameters represent the radii where the density and velocity laws start to change, and the relation R_d ≫ R_c is puzzling, because they should take the same value theoretically. The reason for our finding R_d ≫ R_c can be naturally understood if C^{18}O is less abundant around the center of the clump due to the destruction by the FUV radiation from nearby massive stars (e.g., Shimajiri et al. 2014), or due to the adsorption onto dust in dense regions (e.g., Bergin et al. 2002).

The former effect should be dominant in this case, because, as seen in Figure 1(b), a large fraction of the clump is apparently heated by at least one of the small H II regions (S235A) exhibiting an excitation temperature of >20 K, which should be higher enough for the molecules to evaporate from dust. In addition, there are several intermediate/massive YSOs, including S235AB-MIR, forming around the clump center, which may be the sources of FUVs (see Figure 10 and Table C8 of Dewangan & Anandarao 2011). In any case, note that Equation (1) with the inferred R_d represents the density distribution of the C^{18}O molecules, not necessarily the true total mass of the H_2 molecules. If we assume that the true R_d (for H_2) is the same as the derived R_c (∼6.4 × 10^3 au), the molecular density at the center of the clump should be rescaled to n_0 ∼ 2 × 10^6 H_2 cm^{-3} (instead of 1.1 × 10^5 cm^{-3} in Table 2). We will use these corrected values of R_d and n_0 to estimate physical quantities of the clump in Section 5.

Finally, let us check the validity of our assuming the indices to be α = 1.5, β = 0.5, and γ = 1 in Equations (1)–(3). We adopted these assumptions not only for the consistency with the original Ohashi’s model, but also for a technical reason, to reduce number of the free parameters, because we cannot determine too many parameters within a reasonable amount of calculation time. In order to check their validity, we varied the indices and the other parameters around the best values listed in Table 2 to compare with the observed PV diagrams in Figure 3. We found that the indices minimizing χ^2 are α = 1.5±0.6, β = 0.5±0.2, and γ = 1±0.2, where the uncertainties represent the ranges for the 90% confidence level. Though the uncertainties for α and β are rather large, the results infer that our assumptions for the indices are likely to be plausible.

5. DISCUSSION

Though the angular resolution of our observations is rather limited, the model parameters best fitting the observed data provide us with various important implications on the structures of the clump. For example, Equation (2) with the value of V_{inf} (=1.3 km s^{-1}) should give us an estimate of the mass accretion rate dM_{acc}/dt, i.e., the mass infalling onto or passing through the clump surface per unit time. For the isodensity surface S_2(r) at the characteristic clump radius r = 1.0 × 10^5 au (∼1′ at 1800 pc), an approximation dM_{acc}/dt ∼ ρ S_2 V_{inf} yields 1.2 × 10^{-3} M_⊙ yr^{-1} if we assume R_d = R_c = 6.4 × 10^4 au, suggesting that it would take only ∼1 × 10^5 years to gather the observed clump mass (∼1000 M_⊙) from more diffuse interstellar medium surrounding the clump. In the inner region of the clump, dM_{acc}/dt estimated in this manner stays around ∼1 × 10^{-3} M_⊙ yr^{-1} over a wide range of r down to r = R_c. Note that R_c is the radius where the velocity and density laws start to change and it should be related to the size of the core formed at the center of the clump. The mass enclosed in the derived R_c = 6.4 × 10^4 au is ∼4 M_⊙, and we would expect that a core of this size and mass should be formed at the center of the clump. It is noteworthy that such a dense core has actually been discovered around the most massive star in S235AB located at the center of the clump through molecular and millimeter continuum observations by (Felli et al. 2004, see their Table 4), which may be the direct parent core of the ∼11 M_⊙ star found by Dewangan & Anandarao (2011). Here, we should note that the core size and mass estimated by Felli et al. varies rather largely, taking values in the range 0.03–0.1 pc and 2.3–31 M_⊙, respectively, depending on the tracers they used, which is probably due to the different critical densities of the molecular emission lines as well as due to the ambiguous conversion factors to the total hydrogen column densities. Our estimate of the core mass is also rather ambiguous, and it can vary in the range from ∼0 M_⊙ to ∼12 M_⊙ for the 90% confidence level of R_c in Table 2 (0–9.6 × 10^4 au). Taking these ambiguities into account, we believe that the core found by Felli et al. should correspond to the dense region around the clump center within R_c.
Formation of a massive star at the center of cluster-forming clumps has been studied theoretically by Wang et al. (2010), who performed numerical simulations assuming a massive clump having a mass of 1600 $M_\odot$, similar to S235AB. They found that the most massive member of clusters form at the clump center, which may determine the final size of the clump by blowing away the natal clump. Interestingly, they also found that the mass of the massive star is controlled by the mass of the large-scale natal clump, rather than by the core just around the star, and the mass accretion rate onto the star is regulated by the feedback of an outflow generated by the star.

We should note that Wang et al. (2010) defined the core simply as a 0.1 pc sized sphere in diameter around the central star having no distinguishable dynamical differences compared to the surrounding natal clump, and in that sense, it is not precisely the same core that we discuss here, which follows different density and velocity profiles from the rest of the clump. However, their findings are important, because, if their conclusions are right, the small core found around the central star merely represents the mass transiently trapped around the stellar mass, and the final size of the cluster can be decided mostly by the size (or the infall rate) of the natal clump. Note that, in the case of S235AB, our best estimate for the core mass is only $\sim 4 M_\odot$, while the observed stellar mass is $\sim 11 M_\odot$. Though the uncertainty in our core mass estimate is large, these values suggest that the hypothesis of Wang et al. (2010) can be plausible.

Beside the infalling motion of the clump, there must be ejection of mass by outflows, which should be playing an important role in the cluster-forming clump. They have two major effects in the cluster formation. One is to inject the turbulence to the natal clump, which prevents the clump from collapsing or decelerates the infall velocity, and the other is to release the angular momentum of the mass infalling onto the central star.

Based on the HCO$^+$($J = 1–0$) interferometric observations, Felli et al. (2004) found two candidates of molecular outflows at the center of the clump: one is an outflow with intense blue and red lobes extending toward the NE–SW direction, and the other is a fainter outflow extending toward the NNW–SSE direction (see their Figure 5 and Table 5). We call them the NE–SW outflow and the NNW–SSE outflow in this paper, respectively. Compared with the shape of the clump, the NE–SW outflow is quite puzzling because it is extending along the $x_0$ axis in Figure 3, orthogonal to the rotation axis of the clump. Though there may be some possible mechanisms (e.g., precession of the outflow) to account for the mismatch, we suspect that the NE–SW outflow is not a real outflow, and that its blue and red lobes are tracing something else by chance; for example, the blue lobe could be due to a blueshifted high-velocity gas blowing from the small H II region S235A, and the red lobe could be due to contamination by distinct velocity component(s) unrelated to the clump. We present some observational data to support this possibility in Appendix A.

On the other hand, we believe that the NNW–SSE outflow is a real outflow, not only because it is known to coincide well with a jet traced by water maser spots (Burns et al. 2015), but also because its blue and red lobes are elongating along the rotation axis of the clump (i.e., the $y_0$ axis in Figure 3). The mass ejection rate of the NNW–SSE outflow is estimated by Felli et al. (2004) to be $2.5 \times 10^{-4} M_\odot$ yr$^{-1}$ (see their Table 5), indicating that roughly 20%–30% of the infalling mass derived from our model parameters ($\sim 1 \times 10^{-3} M_\odot$ yr$^{-1}$) are fed back to the natal clump. The 20%–30% feedback of the infalling mass meets well with what we would expect from numerical simulations (Shu et al. 1988; Pelletier & Pudritz 1992). If we include the NE–SW outflow, however, the total mass ejection rate by the two outflows would amount to $\gtrsim 1.55 \times 10^{-3} M_\odot$ yr$^{-1}$ (Felli et al. 2004), which is larger than the infalling mass by $\gtrsim 55\%$. In that case, the clump would be in the final stage of cluster formation being dispersed by the internal outflows, but we suspect that the NE–SW outflow might not be a real outflow, as previously mentioned.

We should also note that the infall velocity with the derived parameter $V_{\text{in}} = 1.3 \text{ km s}^{-1}$ is significantly smaller than the virial velocity calculated as $V_{\text{vir}} = \sqrt{GM/R_0} \approx 4 \text{ km s}^{-1}$, strongly indicating the existence of clump-supporting forces. The injection of turbulence by the feedback of the outflow is a possible source for the deceleration of the infall velocity. It is interesting to note that a density profile of gravitationally stable clumps and free-falling clumps should follow a power law $\rho \propto r^{-\alpha}$ with $\alpha = 2$ and 1.5, respectively, but both of the values are within the uncertainty of our value for $\alpha = (1.5_{-0.2}^{+0.6})$, which may be due to the deceleration of the infalling motion by the clump-supporting forces, including the turbulence generated by the outflow.

The other expected role of the outflow to release of the angular momentum would be probed quantitatively by comparing our model parameter $V_{\text{in}}$ and the angular momentum of the outflow, though the measurement of the outflow rotation is not easy because it requires a very high spatial resolution. We expect that such a measurement can be done by a large interferometer, like ALMA, in near future.

Here, we discuss the major incompleteness of our model. First, we assume a fixed ellipticity $e_0$ for the density distribution. However, while we tried to fit the observed data, we realized that the ellipticity changes along with the radius, being likely to be more flattened in the inner region, which is not taken into account in our model. In addition, for simplicity, we assume that the infall velocities always point toward the center of the clump, which is apparently inappropriate, especially around the center of the clump (e.g., see Figure 2 of Nakamura et al. 1995). Finally, other than the self-gravity, there might be some important sources that should give significant influence on the internal motion of the clump, such as the turbulence and magnetic fields, as well as the feedback from stars forming in the clump, but none of these effects are taken into account in our model, though they may actually give a significant influence on the infalling velocity of the clump as discussed in the above.

Among the possible effects not considered in the present model, the magnetic field is of particular interest, not only because it should affect the shape and velocity fields of the clump by preventing it from collapsing, but also because it may control the star formation rate. Because the clump is actually forming a cluster, we would expect that the clump mass should be larger than the critical mass that can be supported by the magnetic field ($M_{\text{crit}}/M_\odot = 0.13\theta_*/\sqrt{G} \approx 2 \times 10^2 (B/30 \mu G)(R/1 \text{ pc})^2$) (e.g., Nakano 1985; Shu et al. 1987). In that case, the strength of the magnetic field in the clump should be less than $B \approx 900 \mu G$. Although it is difficult to quantify the strength of the magnetic field at the density range of the clump ($10^4$–$10^6$ cm$^{-3}$, e.g., Crutcher et al. 2010),
measurement of the Zeeman splitting of some molecular lines such as CCS ($J = 4_1 - 3_2$) with a sensitive receiver (e.g., Nakamura et al. 2015) would provide us a more precise picture of the cluster-forming clump.

Finally, we should note that the characteristic feature in the PV map, i.e., the two well-defined peaks as seen in Figure 3(b), is often found in massive cluster-forming clumps (T. Shimoikura et al. 2016, in preparation). We therefore suggest that the infalling motion with rotation is a common process in an early stage of cluster formation.

6. CONCLUSIONS

We observed the massive cluster-forming clump S235AB mainly in C$^{18}$O($J = 1-0$) with the 45 m telescope at the Nobeyama Radio Observatory. The observations have revealed that the clump has an elliptic shape having a mass of $\sim$1000 $M_\odot$ and a radius of $\sim$0.5 pc. The C$^{18}$O spectra of the clump often show double-peaks separated by $\sim$1 km s$^{-1}$ and they are symmetrically located with respect to the center of the clump, which can be well recognized as the two well-defined peaks in the PV diagram taken along the major axis of the clump. In addition, there is a slight velocity gradient along the minor axis of the clump. These features seen in the PV diagrams are very similar to those observed toward small dense cores forming single low-mass YSOs, which can be well interpreted as an infalling/collapsing motion of the cores with rotation.

With analogue to a model for single protostars proposed by Ohashi et al. (1997), we made a simple model of the density and velocity distributions of the clump to fit the observed data. The symmetric peaks in the PV diagram measured along the major axis, as well as the velocity gradient along the minor axis, can be reproduced only when we assume an infall motion, and they cannot be reproduced by any sets of the parameters with the infalling velocity $V_{\text{inf}} = 0$, indicating that the cluster-forming clump is actually collapsing toward the clump center. The mass infalling rate inside of the clump is large ($\sim 1 \times 10^{-3} M_\odot$ yr$^{-1}$) and remains rather flat over a large region, and it decreases around the center of the clump at a radius of $\sim$6400 au, suggesting that a small core (with a mass and size of $\sim$4 $M_\odot$ and $\lesssim0.1$ pc) and then a massive star should be formed. Actually, there have been found such a core and a massive star ($\sim$11 $M_\odot$) at the center of the clump by earlier observations. All of these observational facts strongly imply that the clump S235AB should be infalling with rotation following simple kinetic laws in the same way as the cores around single YSOs.

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APPENDIX A

DISTRIBUTIONS OF THE MINOR VELOCITY COMPONENTS

In the observed $^{12}$CO, $^{13}$CO, and C$^{12}$O spectra, the main velocity component tracing the massive clump studied in this work is observed around the velocity $V_{\text{LSR}} \approx -16.7$ km s$^{-1}$. In addition to this main component, there are some other distinct velocity components in the observed region, which we call “minor components” in this paper. The minor components are fainter than the main component, but they are significantly detected, especially in the optically thick $^{12}$CO spectra. In Figure 5, we show the distributions of the minor components. As seen in the figure, there are at least three minor components around the velocities $V_{\text{LSR}} \approx -21$, $-14$, and $-12$ km s$^{-1}$. Their typical spectra are shown in panels (e)–(i). In the following, we will describe these minor components to examine their influence on our analyses in Section 4.

The first minor component at $V_{\text{LSR}} \approx -21$ km s$^{-1}$ is widely seen mainly in the upper-left side of panel (a) of Figure 5, and its enhanced parts are distributed showing an arc-shaped structure around the C$^{18}$O clump studied here (traced by the red contours). It is unclear at the moment whether the minor component has a physical connection with the clump or not, but it is likely to be associated with other larger clouds around the main Sh2-235 H II region located $\sim 10'$ north to the clump, outside the maps in Figure 5 (T. Shimoikura et al. 2016, in preparation). There is another peak at the position labeled B in panel (a) close to the center of the clump. We display spectra observed at this position in panel (h). The $^{12}$CO spectrum in the panel shows a wing-like feature over the velocity range indicated by the vertical broken lines in the panel. This is likely to represent not only this minor component, but also the molecular outflows from the young stars forming there, as well as high-velocity gas blowing from the small H II regions S235A and/or S235B located at $\sim 20''$ away as seen in panel (d). Such a mixture of the outflowing gas from young stars and that blowing from small H II regions has actually been observed in $^{12}$CO in massive star forming regions (e.g., W40, see Shimoikura et al. 2015), and it is generally very difficult to distinguish them clearly in the observed spectra. In the case of our data, a great fraction of the wing-like feature may be due to the high-velocity gas blowing from the two small H II regions, rather than the outflows from young stars, because its spatial distribution in panel (a) tends to delineate the ridge or interface of the H II regions. As mentioned in Section 5, the blue lobe of the NE-SW outflow (Felli et al. 2004) seems to be tracing the ridge of S235A (around the position B), and thus we wonder if the lobes is due to a real molecular outflow or the gas blowing from the H II region (see also Figure 17 of Felli et al. 2004).

Distribution of the second minor component (at $V_{\text{LSR}} \approx -14$ km s$^{-1}$) in panel (b) appears similar to that of the C$^{18}$O clump. Though this is partially because the minor component and the main component (at $V_{\text{LSR}} \approx -16.7$ km s$^{-1}$) are close to each other in velocity and cannot be separated well when generating the map in the panel, we believe that the minor component is also associated with the entire cloud system in this region, because its spatial distribution traces well the distributions of the young stars shown in the panel (d). The minor component is faint in the northern part of the observed region, but it is prominent in the southern part, showing local peaks at positions C and D in panel (b). Velocities of the red lobe of the NE–SW outflow mentioned in Section 5 coincides with this minor component in velocity, and we wonder if the red lobe might be due to a small clump of this component (see also Figure 4 of Felli et al. 2004).

The third minor component (at $V_{\text{LSR}} \approx -12$ km s$^{-1}$) is distributed all over the observed regions as seen in panel (c), exhibiting a large velocity dispersion spreading over
This minor component may not be physically related to the clump studied here. Among the three minor components, the second one at \(-12 \leq V_{LSR} \leq 14 \text{ km s}^{-1}\) can affect our analyses in Section 4, but its influence should be small because the component is very weak in \(^{13}\text{CO}\) over the main part of the clump. An enhancement of the \(^{13}\text{CO}\) emission at \(-14.5 \leq V_{LSR} \leq 15.8 \text{ km s}^{-1}\) and \(x_{0.57} \) in Figure 3(b) should be due to this minor component, but it does not cause significant errors in our analyses, as it is very faint. The other two components at \(-21 \leq V_{LSR} \leq 14 \text{ km s}^{-1}\) should not affect our analyses either, because they are well separated in velocity and are outside the velocity range in Figures 3(b) and (c) used for the analyses. Though we cannot completely rule out the possible contamination by the outflows and/or the high-velocity gas blowing from the H II regions S235A and/or S235B as seen at the position B in Figure 5(a), the \(^{13}\text{CO}\) emission line around the center of the clump is detected only in the velocity range \(-20 \leq V_{LSR} \leq -14.5 \text{ km s}^{-1}\), and thus they are unlikely to give significant influence on our analyses.

**APPENDIX B**

**PV DIAGRAM OF THE \(^{12}\text{CO}\) EMISSION LINE**

Based on the model parameters in Table 2 derived from the \(^{13}\text{CO}\) data, we further attempted to reproduce the observed PV diagrams of \(^{12}\text{CO}\) shown in the upper panels of Figure 6. The diagrams are characterized by the systematically higher blueshifted components compared with the redshifted components.
Our interest here is to investigate if we can reproduce this feature with the model parameters derived from the C$^{18}$O data, which will provide another support for the infalling motion of the rotating clump.

Unlike in the case of C$^{18}$O, it is not easy to model the PV diagrams of $^{12}$CO precisely, because the line is very optically thick and the shape of the emission line could be easily affected by the assumption on the 3D distribution of the excitation temperature $T_{\text{ex}}$, which cannot be determined well. Because the 2D distribution of $T_{\text{ex}}$ peaks at one of the small H II regions S235A, as seen in Figure 1(b), and also because the H II region appears rather obscured on optical images such as DSS, we believe that S235A should be located rather in the back of the clump and should dominate the overall distribution of $T_{\text{ex}}$ around the clump. We therefore assume the distribution of $T_{\text{ex}}$ in 3D as

$$T_{\text{ex}} = \frac{2T_0}{1 + \sqrt{r' / R_T}},$$

where $T_0$ and $R_T$ are constants, and $r'$ is the distance to the center of the H II region located at $(x_0, y_0) = (x_{\text{H II}}, y_{\text{H II}}, z_{\text{H II}})$ in the $(x, y, z)$ coordinates in Figure 4. The apparent center of the H II region is $(x_0, y_0) \simeq (-25'', -12'')$ on the observer’s axes, but its precise location along the line of sight (i.e., the $z_0$ axis) is unknown. We therefore tentatively assume $(x_{\text{H II}}, y_{\text{H II}}, z_{\text{H II}}) \simeq (-25'', -15'', -20'') \simeq (-4.5 \times 10^4, -2.7 \times 10^4, -3.6 \times 10^4)$ au at the distance 1800 pc. We also assume $T_0 = 120$ K and $R_T = 7''5 = 1.35 \times 10^4$ au, which

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**Figure 6.** Upper panels: observed position–velocity diagrams of the $^{12}$CO emission line (color scale) measured along the cuts 1–1’ and 2–2’ in Figure 3. Lower panels: same as the upper panels, but for the simulated $^{12}$CO spectra (see Appendix B). For comparison, contours for the position–velocity diagrams of $\text{H}_2$ displayed in Figure 3 are overlaid. White arrows indicate the blueshifted $^{12}$CO emission exhibiting higher temperature that can be reproduced only when we assume the infalling motion of the clump.
reproduces the observed 2D distribution of $T_{\text{ex}}$ in Figure 1(b) well.

Using the clump parameters listed in Table 2, we calculated the expected $^{12}$CO spectra at each line of sight in the same way as we did for the C$^{18}$O data in Section 4, but by solving the radiative transfer taking into account the optical depth estimated for a $^{12}$CO fractional abundance of $1 \times 10^{-4}$ (Frerking et al. 1982), and resampling the spectra on the same grid with the same angular resolution as those of the observations.

Resulting PV diagrams are compared with the observed ones in the Figure 6. Though there are some arbitrary parameters, such as the location of the H II region ($z_{\text{H}}$), the observed higher blueshifted components both along the major and minor axes of the clump are reproduced well by the above calculations. We should note that, like in the case of C$^{18}$O, the observed higher temperature in the blueshifted components in the PV diagrams of $^{12}$CO can be reproduced only when we assume the infalling motion of the clump ($V_{\text{inf}} = 0$). It is also noteworthy that we calculated the PV diagrams for some different values of $T_{b}$, $R_{t}$, and $(x_{\text{H}}, y_{\text{H}}, z_{\text{H}})$ to find that the important features in the PV diagrams do not change qualitatively for small variations of these parameters.

In Figure 6, however, there are some noticeable differences between the observed and simulated PV diagrams. The observed blueshifted components along the major axis in panel (a) (indicated by the arrow) are more widely distributed in velocity than the simulated ones in panel (c). This is due to our imposing a constant velocity dispersion of $\Delta V = 1.8 \text{ km s}^{-1}$ in the same way as for the C$^{18}$O data in Section 4. We would obtain a simulated PV diagram more similar to the observed one if we impose a larger velocity dispersion, which would obtain a simulated PV diagram more similar to the observed blueshifted components along the major axis in panel (a). The bumps are apparently due to the minor velocity component ($-14 \text{ km s}^{-1}$) mentioned in Appendix A, which is not taken into account in our calculations.

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