A Low-velocity Bipolar Outflow from a Deeply Embedded Object in Taurus Revealed by the Atacama Compact Array

Kakeru Fujishiro1, Kazuki Tokuda2,3, Kengo Tachihara1, Tatsuyuki Takashima2, Yasuo Fukui1,4, Sarolta Zahorecz2,3, Kazuya Saigo3, Tomoaki Matsumoto5, Kengo Tomida6, Masahiro N. Machida7, Shu-ichiro Inutsuka1, Philippe André8, Akiko Kawamura3, and Toshikazu Onishi2

1 Department of Physics, Nagoya University, Chikusa-ku, Nagoya 464-8606, Japan
2 Department of Physical Science, Graduate School of Science, Osaka Prefecture University, 1-1 Gakuen-cho, Naka-ku, Sakai, Osaka 599-8531, Japan
3 National Astronomical Observatory of Japan, National Institutes of Natural Science, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
4 Institute for Advanced Research, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8606, Japan
5 Faculty of Sustainability Studies, Hosei University, Fujimi, Chiyoda-ku, Tokyo 102-8160, Japan
6 Astronomical Institute, Tohoku University, 6-3, Aramaki, Aoba-ku, Sendai, Miyagi 980-8578, Japan
7 Department of Earth and Planetary Sciences, Faculty of Sciences, Kyushu University, Nishi-ku, Fukuoka 819-0395, Japan
8 Laboratoire d’Astrophysique (AIM), CEA, CNRS, Université Paris-Saclay, Université Paris Diderot, Sorbonne Paris Cité, France

Abstract

The first hydrostatic core, the first quasi-hydrostatic object formed during the star formation process, is still the observational missing link between the prestellar and protostellar phases, mainly due to its short lifetime. Although we have not established a clear method to identify this rare object, recent theoretical studies predict that the first core has millimeter continuum emission and low-velocity outflow with a wide opening angle. An extensive continuum/outflow survey toward a large number of “starless” cores in nearby star-forming regions works as a pathfinder. We observed 32 prestellar cores in Taurus with an average density of \( \gtrsim 10^7 \text{ cm}^{-3} \) in 1.3 mm continuum and molecular lines using the Atacama Large Millimeter/submillimeter Array–Atacama Compact Array (ALMA–ACA) stand-alone mode. Among the targets, MC35-mm centered at one of the densest “starless” cores in Taurus has blueshifted/redshifted wings in the \(^{12}\text{CO} (2\rightarrow 1) \) line, indicating that there is a deeply embedded object driving molecular outflow. The observed velocities and sizes of the possible outflow lobes are 2–4 km s\(^{-1} \) and \( \sim 2 \times 10^4 \) au, respectively, and the dynamical time is calculated to be \( \sim 10^3 \) yr. In addition to this, the core is one of the strongest \(^2\text{HDO}^+ (3\rightarrow 2) \) emitters in our sample. All of the observed signatures do not conflict with any of the theoretical predictions about the first hydrostatic core so far, and thus MC35-mm is unique as the only first-core candidate in the Taurus molecular cloud.

Unified Astronomy Thesaurus concepts: Collapsing clouds (267); Protostars (1302); Star formation (1569)

1. Introduction

Understanding of the low-mass star formation process has been intensively studied from decades ago, mainly by theoretical work at the beginning (e.g., Larson 1969; Shu 1977; Shu et al. 1987; Inutsuka 2012). They explained that the fragmentation and condensation of molecular clouds result in forming dense cores, which undergo gravitational collapse to form stars. According to the theoretical studies, dense cores eventually harbor the first protostellar cores, the first quasi-hydrostatic object during the star formation process (hereafter the first core; e.g., Larson 1969; Masunaga et al. 1998; Tomida et al. 2013), which provide the initial condition of star formation. Recent magnetohydrodynamic (MHD) simulations demonstrated that the first core has a size of 1–100 au is formed when the central density exceeds \( \sim 10^{10} \text{ cm}^{-3} \) via the gravitational collapse. The first core is suggested to have a low-velocity (1–10 km s\(^{-1} \)) molecular outflow with a wide opening angle (Machida et al. 2008), which is qualitatively different from the collimated jet driven by a mature protostar. However, it is difficult to identify such an object observationally because the first core has a short lifetime, \( 10^3–10^4 \) yr, depending on the physical condition of the parental core (Tomida et al. 2010), and does not show bright infrared emission. Although some candidates of the first core were already reported in the past decade (e.g., Chen et al. 2010, 2012; Enoch et al. 2010; Pineda et al. 2011; Pezzuto et al. 2012; Hirano & Liu 2014), the first-core phase is not fully explored observationally and it is supposed to still be the missing link between the isothermal and adiabatic collapse (i.e., prestellar and protostellar core). To search for candidates of the first core, it is essential to perform a survey-type observation toward a large number of starless cores. According to the early dense core survey with an average density of \( \gtrsim 10^7 \text{ cm}^{-3} \) (Onishi et al. 2002), the lifetime of the starless phase is \( \sim 4 \times 10^5 \) yr (see also Ward-Thompson et al. 2007). The simple calculation tells us that only one out of a few \( 10–100 \) cores harbors the first core(s).

The Taurus molecular cloud complex (e.g., Kenyon et al. 2008) is one of the best-studied low-mass star-forming regions, and there is a dense core catalog (Onishi et al. 2002), which was sampled by an unbiased large-scale molecular gas survey. We carried out an Atacama Large Millimeter/submillimeter Array (ALMA) survey, \( \text{FRA} \)gmentation and Evolution of dense cores Judge by ALMA (FREJA), toward the dense cores in Taurus using the Atacama Compact Array (ACA). Tokuda et al. (2020, hereafter Paper I) described the observation settings and early results obtained by the 1.3 mm continuum emission. In this Letter, we explain the detailed results of a dense core L1535-NE/MC35, harboring a possible candidate of the first core.
2. Observations and Descriptions of the Target Object, L1535-NE/MC35

As the detailed observational properties of this project are given in Paper I, thus we summarize the data qualities of the target briefly. The angular resolution is $6.8^\prime \times 6^\prime$, corresponding to 850 au $\times$ 730 au at a distance of 126.6 pc (Galli et al. 2018). The frequency settings contain the 1.3 mm continuum emission and molecular lines of $^{12}\text{CO}$, $^{13}\text{CO}$, $^{18}\text{O}$ (2–1), and $N_2D^+$ (3–2). The rms sensitivities of the continuum and lines are $\sim$0.4 mJy beam$^{-1}$ and $\sim$0.9 mJy beam$^{-1}$ ($\sim$0.05 K) at a velocity resolution of $0.1 \text{ km s}^{-1}$, respectively. We use the combined 7 m + Total Power (TP) array data to recover the extended emission of $^{12}\text{CO}$ (Section 3.1), while for $N_2D^+$ we use the 7 m array data alone to be compared with the compact 1.3 mm source (Section 3.2).

The target object, L1535-NE (also know as MC35; see Onishi et al. 2002), is located in the Barnard18 region in Taurus. Hogerheijde & Sandell (2000) found an intensity enhancement in the submillimeter continuum emission, observed by James Clerk Maxwell Telescope (JCMT)/SCUBA at 850 $\mu$m and with Institut de radioastronomie millimétrique (IRAM) 30 m/MAMBO at 1.2 mm by Motte & Andrè (2001) next to the previously know protostar IRAS 04325+2402, which is a Class I source with multiplicity (Hartmann et al. 1999). The nondetection of infrared point sources at the center of the dense core MC35 by the IRAS deep survey (Beichman et al. 1992) means that there is no bright source with an upper limit of $\sim$0.1 $L_\odot$. We checked the archival data of Herschel and Spitzer and confirmed the nondetection of point sources at wavelengths shorter than 70 $\mu$m. The derived dust temperature is as cold as 10–15 K (Hogerheijde & Sandell 2000), and the previous molecular gas survey in $^{12}\text{CO}(1–0)$ with Five College Radio Astronomical Observatory (FCRAO) could not find an outflow from this object (Narayanan et al. 2012). These observational signatures are consistent with the fact that there is no associated mature young stellar object. The single-dish observations found that this core has strong molecular line emission of high-density gas tracers, H$^{13}\text{CO}$, $N_2H^+$, and $N_2D^+$ (Onishi et al. 2002; Tobin et al. 2013), indicating that there is a density enhancement at the dust continuum peak. Figure 1 illustrates the observed area, the 1.2 mm continuum emission by the IRAM 30 m telescope, and infrared images by the Spitzer. The observed central coordinate was $(\alpha_{2000.0}, \delta_{2000.0}) = (4^h 35^m 37^s 15, +24^d 09^m 17^s 00)$.

3. Results

3.1. Possible Compact Molecular Outflow at the Dust Continuum Peak

Figure 2(a) shows the 1.3 mm continuum emission toward MC35. We call the millimeter source “MC35-mm” hereafter. Based on the two-dimensional Gaussian fitting to it, the central coordinate and deconvolved size are derived to be $(\alpha_{2000.0}, \delta_{2000.0}) = (4^h 35^m 37^s 87, +24^d 09^m 19^s 8)$. The peak position coincides with that obtained by IRAM 30 m (Motte & Andrè 2001). This result means that the ACA observations traced the innermost part of the mass distribution. The peak and total continuum fluxes obtained by the ACA are 2.8 mJy beam$^{-1}$ and 7.8 mJy, respectively. Although the continuum flux is not the strongest one among our targets, we detect the strongest $N_2D^+$ emission with a peak brightness temperature of $\sim$0.5 K at MC35-mm (Figure 2(b); see also Section 3.2). This result means that there is a density enhancement at the position.

To find molecular outflows from deeply embedded objects, we investigated $^{12}\text{CO}$ data toward the continuum-detected prestellar cores. Thus, we searched for high-velocity wing components more than a few km s$^{-1}$ apart from the systemic velocity as the excess emission to the Gaussian-like spectral profile by eye. As a result, we found that MC35-mm has
indications of wing components. Figure 2(a) shows the distributions of the high-velocity wing components in $^{12}$CO. As one can see, there are bipolar conical-shaped features of the blue/redshifted components, and they seem to be connected to the millimeter continuum peak. In the channel maps (Figure 3), this nature is also well represented, especially at 4.2–4.6 km s$^{-1}$ for the blue component and 7.9–8.3 km s$^{-1}$ for the red one. Figure 2(b) illustrates the velocity profiles of the $^{12}$CO emission. The selected velocity ranges of the blueshifted and redshifted components are 3.5–4.7 km s$^{-1}$ and 7.5–10.0 km s$^{-1}$, respectively. We could not detect significant $^{13}$CO emission in these velocity ranges. We can see clear line broadening up to $\sim$4 km s$^{-1}$ with respect to the systemic velocity. Because the turbulence of this source ($\Delta V \sim 0.3$ km s$^{-1}$; see Tobin et al. 2013) cannot produce such relatively high-velocity emission, there should be a driving source. The wing components are likely molecular outflow from a deeply embedded object inside MC35-mm. We found the blueshifted gas at the south side of the continuum peak, while there are two redshifted components at both the north and south sides. If the outflow is viewed away from pole-on, and it has a wide opening angle, the geometric effect can explain the present configuration. We could not find the blueshifted component at the northern side, possibly because the emission is very close to the systemic velocity with serious contaminations of the extended emission.

We characterize the possible molecular outflow components. We defined the velocity difference between the central velocity of the $N_2D^+$ profile (5.9 km s$^{-1}$) and the edges of the wing emission in $^{12}$CO (Figures 2(b), (c)) as its maximum velocities. The sizes of the wing components are the distances between the peak position of MC35-mm and the peak of the blue/red contours in Figure 2(a). Table 1 summarizes the derived parameters from the observed values with an assumption of the inclination angles of the outflows as 30° and 70° with respect to the line of sight.

The resultant dynamical time (=size/velocity) of the wing is $\sim$(1–6) $\times$ 10$^5$ yr. We estimated the masses of the wing components assuming the local thermodynamical equilibrium with a uniform excitation temperature of 20 K and $^{12}$CO/H$_2$ = 10$^{-4}$, following the equations written by Pineda et al. (2011). We further discuss these parameters in Section 4.1.

3.2. Dense Gas Distributions Traced by the $N_2D^+$ Emission

Figure 4 shows the distributions of $N_2D^+(3–2)$. The peak position of the velocity-integrated intensity (moment 0) image corresponds to that in 1.3 mm, indicating MC35-mm is in a cold/dense state, which is similar to evolved prestellar cores (e.g., Caselli et al. 2002). The intensity-weighted mean velocity (moment 1) map of $N_2D^+$ (Figure 4(b)) marginally shows a velocity gradient from the northeast to the southwest, which is roughly perpendicular to that of the wing components (Section 3.1). This feature may represent that there is a rotating component at MC35-mm.

4. Discussions

4.1. Is MC35-mm a Candidate of the First Core?

We found possible outflow lobes at one of the densest “starless” cores in Taurus. Before discussing the nature of the source, we mention the possibility of contamination emission by the nearby protostar, IRAS 04325+2402. As shown in Figure 1, there is a bipolar scattered-light nebula centered at the protostar. Based on the Spitzer image, the dense region of MC35 seems to be illuminated by the scattered light. Although some previous studies reported a parsec-scale redshifted CO outflow from the protostellar system (e.g., Heyer et al. 1987; Narayanan et al. 2012), its direction is inconsistent with that of the scattered-light bipolar nebula (see the red arrow in Figure 1(b)). The Submillimeter Array (SMA) observation by
Figure 3. Color-scale images and white contours show velocity-channel maps of the 7 m + TP $^{13}$CO(2-1) data toward MC35-mm. The lowest contour level and subsequent steps are 0.06 K km s$^{-1}$. The black contours of each panel are the same as those in Figure 2(a). The upper-left corner of each panel gives the integrated velocity ranges. The filled ellipses in the lower-left corner of the upper-left panel show the synthesized beam size.

Table 1
Outflow Properties

|                  | Blue | South | Red | North |
|------------------|------|-------|-----|-------|
| Inclination angle (deg.) | obs. | 30    | 70  | obs.  | 30  | 70  | obs. | 30  | 70  |
| Maximum velocity (km s$^{-1}$) | 2.3  | 2.7   | 6.7 | 4.2   | 4.8 | 12.3| 4.2  | 4.8  | 12.3 |
| Size (10$^3$ au)   | 1.5  | 3.0   | 1.6 | 2.1   | 4.2 | 2.2 | 1.6  | 3.1  | 1.6  |
| Dynamical time (10$^3$ yr) | ... | 5.7   | 1.2 | ...   | 4.3 | 0.9 | ...  | 3.2  | 0.7  |
| Mass (10$^{-5}$ $M_\odot$) | 0.6  | ...   | ...| 1.2   | ... | ...| 2.0  | ...  | ...  |
Scholz et al. (2010) has detected compact high-velocity CO components with a size of a few hundred au, whose elongation is roughly consistent with the scattered-light nebula. The scattered-light nebula traced by mid-infrared observations and molecular outflow distribution do not necessarily match completely, as discussed by Tobin et al. (2010) and Tokuda et al. (2016). Moreover, the bipolar feature of the newly detected wing components is hard to explain as an outflow lobe from another protostar. In summary, we conclude that the wing components are not just arising from the contamination of the protostellar activity in the southern part.

We estimate that the dynamical time of the outflow is approximately \((1–6) \times 10^3\) yr, depending on its inclination angle (see Section 3.1). This outflow is possibly the youngest one among other very low-luminosity objects (VeLLOs) or first-core candidates (Dunham et al. 2011). The outflow velocity is not high compared to the typical low-mass protostar \((\gtrsim 10\) km s\(^{-1}\); e.g., Hogerheijde et al. 1998), and the distribution shows a wide opening angle. These observational properties are consistent with that of another first-core candidate, L1451-mm (Pineda et al. 2011), and the theoretical simulations, as mentioned in the 1. The presence of the \(N_2D^+\) emission (Section 3.2) can be a key piece of evidence as a young phase. If there is a mature protostar, the \(N_2D^+\) abundance rapidly decreases as the gas temperature +\(\sim 10^3\) K, and a clear position discrepancy between the \(N_2D^+\) and continuum peaks. These features strongly indicate the absence of a mature protostar here, and thus we conclude that the MC35 core harbors a “candidate” of the first core. The Herschel Gould Belt survey (André et al. 2014) detected the 100 \(\mu m\) emission with an integrated luminosity of \(~0.6\) Jy, which is consistent with that of theoretical predictions (Tomida et al. 2010) and also comparable to the low-luminosity Class 0 source (e.g., André et al. 1999). The only concern is that the 100 \(\mu m\) peak does not completely match the ACA 1.3 mm peak and is \(~16^\circ\) closer to the IRAS source.

We compare the evolutionary stage of MC35 with that of other condensations just before/after star formation in Taurus. IRAM 041911+1522 is a low-luminosity \((\sim 0.08\) \(L_\odot\)) protostar (Dunham et al. 2006). André et al. (1999) found the highly collimated CO outflow, and they concluded that the source is considered to be a very young accreting class 0 protostar. Although MC27/L1521F was formerly categorized as a first-core candidate (Mizuno et al. 1994; Onishi et al. 1999), Spitzer observations revealed that the dense core harbors a protostar whose internal luminosity is \(~0.05\) \(L_\odot\) (Bourke et al. 2006). The subsequent ALMA studies found that the protostellar mass is \(~0.2\) \(M_\odot\) without current mass accretion activity (Tokuda et al. 2017), and thus the protostar is more evolved than the first-core stage. L1544, which shares several similar properties with MC27/L1521F (Crapsi et al. 2004), is famous for a prototypical prestellar core. Although recent ALMA 12 m array observations (Caselli et al. 2019) confirmed the centrally concentrated nature of the source, there is no report on the outflow so far. Among our starless sample in the ACA survey, MC35N has the strongest continuum emission (Paper I), and we suggested that this core is a highly evolved stage on the verge of brown dwarf/very low-mass star formation (Tokuda et al. 2019). We could not detect the outflow toward MC5N as well, and the evolutionary stage is considered to be younger than MC35 and close to L1544. In summary, we suggest that MC35-mm is a unique source as the only first-core candidate in the Taurus region.

Note that it is observationally difficult to distinguish between the first core and VeLLO (see the review by Dunham et al. 2014) so far; we need follow-up high-resolution studies to clarify the evolutionary stages, for example, by estimating the mass of the central object, as demonstrated by recent ALMA observations toward VeLLOs (Tokuda et al. 2017; Lee et al. 2018).
4.2. Lifetime of the First-core Candidate

The single-dish survey in Taurus found that there are ∼50 prestellar cores with an average density of ∼10^3 cm^-3, and their lifetime is (4–5) × 10^3 yr (Onishi et al. 2002; Paper I). Because the theoretically predicted lifetime of the first core is typically ∼10^3 yr (e.g., Larson 1969; Saigo & Tomisaka 2006), it is no wonder that no candidates are found within dozens of targets. However, our survey toward ∼30 prestellar cores in Taurus detected at least one promising candidate of the first core. This result observationally gives us a lifetime of the first core, ∼10^4 yr, which is tentatively consistent with the dynamical time of the outflow lobes. Some theoretical studies suggested that the statistical lifetime of the first core can be longer than 10^4 yr in the case of the gravitational collapse of a sub-solar-mass condensation (e.g., Saigo & Tomisaka 2006; Tomida et al. 2010; Stamer & Inutsuka 2018). Although the core MC35 itself is as massive as ∼6–11 M⊙ (Motte & André 2001; Onishi et al. 2002), there is a possibility that the collapsing region is small. In fact, the parental core already forms the protostellar system, IRAS 04325+2402, suggesting that the core fragmented into two pieces by some mechanism, and then the southern part collapsed locally.

We discuss the possibility of a regional difference in the lifetime of the first core. Recent systematic investigations toward Perseus by Stephens et al. (2019) using SMA reported that 6 of the 74 observed prestellar targets were suggested to be first-core candidates. Note that not all of the 74 targets were confirmed to be prestars because they could not detect 1.3 and/or 0.85 mm continuum emission toward several sources (see their Table 7). They also discussed that at least two sources are relatively unlikely as the first-core candidates. The total number of the protostars can be revised into ∼70, and 4 of them are first-core candidates. If we assume that the Class 0/I phase lasts 0.5 Myr (e.g., Dunham et al. 2014), the inferred lifetime of the first-core (candidate) phase is ∼3 × 10^4 yr (=0.5 Myr *4/70), which is significantly longer than the theoretically expected time. We thus speculate that some of the samples should contain more mature protostars or be in a prestellar phase. If only one source in Perseus is the first core, the inferred lifetime is less than 10^4 yr, which is consistent with that of our Taurus result. As suggested by Stephens et al. (2019), L1451-nm is the best candidate in Perseus.

If the Perseus candidates are all genuinely a first core, the environment may play a vital role in extending the first-core phase. In general, low-mass cluster-forming regions show fragmented core distributions and highly turbulent gas kinetics (see Tachihara et al. 2002; Ward-Thompson et al. 2007) compared to those in isolated star-forming region, like Taurus. From a theoretical perspective, rotation of a parental core can work to extend the first-core phase (Saigo & Tomisaka 2006). If the more turbulent environment forms a larger number of sub-solar-mass cores (Enoch et al. 2006) with rapid rotation, this can explain the lifetime difference in the first-core phase between the two regions. However, our current observational understanding regarding the first-core candidates is still incomplete. Detailed follow-up observations using millimeter/submillimeter interferometric facilities will allow us to understand the true nature of such candidates further.

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