A Very Dense Low-Mass Molecular Condensation in Taurus: Evidence for the Moment of Protostellar Core Formation

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(Rceived 1998 November 10; accepted 1998 March 1)

Abstract

We present evidence for a protostellar condensation that is very close to the moment of the formation of a protostellar core within a time scale of ~ 10^4 yr. This starless condensation, named MC 27 in complete surveyed molecular condensations in Taurus, is ~ 0.1 pc in size and ~ 3M⊙ in mass. It exhibits fairly strong and narrow H^{13}CO^+ emission of the J = 4-3, 3-2, and 1-0 transitions, as well as self-reversed profiles of HCO^+ J = 4-3 and 3-2. MC 27 has a density of ~ 10^6 cm^{-3} within ~ 1000 AU at the center, which is the highest value among the ~ 40 starless condensations in Taurus. MC 27 shows a sharply peaked density distribution; the molecular intensity is well fitted by a power-law density distribution of r^{-2} over 0.02 pc < r < 0.2 pc. A statistical analysis indicates a very short time scale of ~ 10^4 yr, which is consistent with a free-fall time scale for a density of ~ 10^6 cm^{-3}. These properties strongly suggest that MC 27 is in a very early stage of star formation. A Monte Carlo simulation of the present profiles indicates that the infall velocity at 2000-3000 AU should be 0.2-0.3 km s^{-1} while it is less than 0.3 km s^{-1} at < 1000 AU. This derived infall velocity profile can be explained by a dynamical-collapse model of supercritical condensation prior to formation of the first protostellar core by ~ 10^{3.4} yr.

Key words: Interstellar: clouds — Interstellar: molecules — Line profiles — Stars: formation

1. Introduction

Astronomers’ efforts toward understanding of star formation have been sharply focused on detecting an extremely early stage of protostar formation in a dense molecular condensation. Stars are formed in dense molecular condensations, that can be detected only in molecular line or dust continuum emission at millimeter or sub-millimeter wavelengths (e.g., Benson, Myers 1989; Fukui et al. 1991; Mizuno et al. 1994; Fukui, Yonekura 1997; Onishi et al. 1998). Mizuno et al. (1994) argued that such condensations are collapsing in a time scale of a few x 10^5 yr from the fact that starless cores are on average a factor of ~ 3 times smaller in size than those with embedded stars.

Fairly young protostars formed in them have been observed as molecular outflows and are sometimes designated as Class I or Class 0 objects whose evolutionary time scale is likely in the order of 10^5 yr (e.g., Lada 1987; Fukui et al. 1989; Andre et al. 1993). In millimeter molecular emission, recent observations toward such objects have revealed asymmetric self-absorbed line profiles that are plausibly explained in terms of infall motion (e.g., Zhou et al. 1993), and high-resolution interferometric observations suggest spatially resolved infall signatures (e.g., Hayashi et al. 1993; Ohashi et al. 1997; Momose et al. 1998).

On the other hand, a study of the moment of protostar formation whose time scale is < 10^4 yr has not yet been done because of the difficulty of detecting such a rare event. While theoretical studies of the collapse of a molecular condensation predict how molecular gas begins to contract dynamically to form a protostar (Boss, Yorke 1995), there has been no observational study of such an extremely early stage of protostellar collapse to constrain the model. Here, we report on the detection of a low-mass protostellar condensation that is likely to be very close to the moment of the formation of a protostellar core within a time scale of ~ 10^4 yr, and discuss the astrophysical implications.

2. Observations

Our recent complete search for molecular gas condensations in Taurus has revealed ~ 40 dense molecular condensations without any star-formation activity in the H^{13}CO^+ J = 1-0 (Onishi et al. 1998; Onishi et al. in preparation). Early results of the survey have been published elsewhere (Mizuno et al. 1994). We observed nine H^{13}CO^+ J = 1-0 starless condensations that have the highest integrated intensities among these condensations in the J = 4-3 and 3-2 lines of both HCO+ and H^{13}CO+. © Astronomical Society of Japan • Provided by the NASA Astrophysics Data System
The observations were made on 1996 August 26-29 using the 10.4-m telescope at the Caltech Submillimeter Observatory (CSO). The beam sizes of the J = 4-3 and J = 3-2 lines are ~ 24" and 32", respectively. The beam efficiencies are 65% and 76%, respectively. The rms noise temperatures per channel for the HCO$^+$ J = 4-3, 3-2, H$^{13}$CO+ J = 4-3, and 3-2 are ~ 0.1, ~ 0.1, ~ 0.08, and ~ 0.05 K, respectively.

3. Results

3.1. Summary of the Present Search

We detected H$^{13}$CO$^+$ J = 3-2 emission only for 4 condensations whose H$^{13}$CO$^+$ J = 1-0 antenna temperature exceeds 1 K. On the other hand, we did not detect H$^{13}$CO$^+$ J = 4-3 emission toward any starless condensations. The intensity of these H$^{13}$CO$^+$ lines appears to be a good indicator of the molecular density, since the line is excited only at a density of $> 10^{5.6}$ cm$^{-3}$. The intensity of the H$^{13}$CO$^+$ J = 3-2 line is in fact found to be well correlated with that of the H$^{13}$CO$^+$ J = 1-0 line. A radiative-transfer model employing the Large Velocity Gradient (LVG) approximation (Goldreich, Kwan 1974) is used to estimate the density in the central 2000 AU of these condensations for the three optically thin transitions of H$^{13}$CO$^+$. As a result, MC 27 (Molecular Condensation 27), which is the 27-th condensation in our catalog, is found to have the highest density of $(8\pm1) \times 10^5$ cm$^{-3}$, significantly larger than those of the other starless condensations of $(1-2) \times 10^5$ cm$^{-3}$. This result strongly suggests that MC 27 is the most evolved starless condensation in Taurus. In order to pursue the evolutionary status of MC 27, we describe the detailed characteristics of MC 27 and discuss the implications on the process of star formation in the following.

3.2. Characteristics of MC 27

MC 27 is located in the middle of the Taurus cloud complex, between the HLC 2 and L1495 regions. This object was discovered in the early stage of a search for molecular condensations in H$^{13}$CO$^+$ J = 1-0 emission, as listed in table 1 (no. 3) of Mizuno et al. (1994). It has no far-infrared counterpart in the IRAS point-source catalog. We also checked the IRAS images and confirmed that the luminosity of the point source is less than 0.1 $L_\odot$ if it exists. This indicates that a star is not yet formed, or that the formed star is very young, emitting only a small amount of radiation energy compared to that of a mature protostar. This condensation is embedded in a C$^{18}$O core isolated from the other C$^{18}$O cores (Onishi et al. 1996, 1998), and this C$^{18}$O core is surrounded by nearly uniform low-density gas of $10^3$ cm$^{-3}$, as observed in the $^{13}$CO J = 1-0 emission (Mizuno et al. 1995).

Figure 1 shows the $^{13}$CO, C$^{18}$O, and H$^{13}$CO+ J = 1-0 integrated intensity maps of MC 27 (Mizuno et al. 1994; Mizuno et al. 1995; Onishi et al. 1996, 1998). These maps indicate that MC 27 has a nearly circularly symmetric shape from the low-density region of $10^3$ cm$^{-3}$ up to the high-density region of $10^5$ cm$^{-3}$. The integrated intensity distribution of C$^{18}$O and H$^{13}$CO+ J = 1-0 can be fitted by a single power-law ranging in the form of TV ~ $r^{-0.9\pm0.2}$ and $N ~ r^{-0.8\pm0.1}$, respectively, for $0.02 < r < 0.2$ pc after correcting for beam dilution. If we take into account its symmetric shape, it is likely that the density distribution follows a power law of $r^{-1.8-1.9}$ whereas the index values of a typical starless condensation are ~ (1-1.5) (Ward-Thompson et al. 1994; Tafalla et al. 1999). MC 27 therefore shows the steepest density
distribution among starless condensations.

Figure 2 shows the spectra of HCO$^+$ J = 3-2, 4-3 and H$^{13}$CO$^+$ J = 1-0, 3-2, 4-3 obtained toward the center of MC 27. The broad and asymmetric profiles of the HCO$^+$ J = 3-2 and 4-3 lines indicate a large optical depth and self-absorption due to the foreground gas. This self-absorption is likely to be caused by dense gas of $n$(H$_2$) $\sim$ 10$^5$ cm$^{-3}$, physically associated with MC 27. The HCO$^+$ J = 3-2 line has apparent wing-like velocity components at $V_{lsr}$ < 5.8 and $V_{lsr}$ > 7.4 km s$^{-1}$. The profile maps of HCO$^+$ J = 3-2 in figure 3 show that the wing-velocity components are seen only toward the center. On the other hand, the J = 1-0 and 3-2 spectra of less-abundant H$^{13}$CO$^+$ have single and narrow profiles of line width $\Delta v$ $\sim$ 0.6 km s$^{-1}$, comparable to that of the others without stars, while the J = 4-3 emission is not detected with the present sensitivity. The profile maps of H$^{13}$CO$^+$ J = 3-2 in figure 3 show that the high-density region is very compact within < 15" of the H$^{13}$CO$^+$ J = 1-0 peak, i.e., < 2000 AU.

4. Analysis and Discussion

The asymmetric profile with a brighter blue peak of the HCO$^+$ profiles is qualitatively explicable by an infall motion in a collapsing spherical cloud (Zhou et al. 1993). In order to test quantitatively how the infall model is applicable to MC 27, we carried out a model fitting using Monte Carlo simulations (Bernes 1979). In the fitting, we assumed a spherical model of uniform HCO$^+$ abundance and kinetic temperature. The radius was assumed to be 2', corresponding to 16000 AU, and the sphere was divided into 60 shells at regular intervals. Because MC 27 does not include protostars of luminosity $>$ O.IL®, the assumption concerning the temperature seems to be plausible. We also assume a density gradient of $n$(H$_2$) $\sim$ $r^{-2}$ based on the observed gradient of the column density and a density of 10$^6$ cm$^{-3}$ at 1000 AU. Under these assumptions, we calculated the HCO$^+$ and H$^{13}$CO$^+$ profiles smoothed to the beam size for a variety of velocity
somewhat lower than that in the center of H$^{13}$CO$^+$ condensation, in order to fit the average intensities of the wings. This suggests that there are two components within ~1500 AU from the center; one is gas of high density (~10$^6$ cm$^{-3}$) with a small velocity (<0.3 km s$^{-1}$); the other has a lower density (<5 x 10$^4$ cm$^{-3}$) with a higher velocity (~1 km s$^{-1}$). If the wing is due to infall, the density of the wing must be much higher than the present value. Moreover, the present model cannot reproduce this wing as infall, because the large infall velocity of ~1 km s$^{-1}$ inside ~2000 AU requires H$^{13}$CO$^+$ spectra with a larger line width. Therefore, this wing is probably due to outflow. The asymmetry of the wing is also consistent with this.

As discussed above, MC 27 is unique among the starless condensations in Taurus. Especially, it has the largest density of ~10$^6$ cm$^{-3}$, significantly higher than that of the other present starless condensations, ~10$^5$ cm$^{-3}$, typical of the low-mass star-forming regions. This suggests that MC 27 is the most evolved starless condensation in terms of gravitational collapse. The free-fall time scale at 10$^6$ cm$^{-3}$ is quite short, a few x 10$^4$ yr, indicating that the evolutionary stage of MC 27 is very short-lived. Assuming a constant star-formation rate during the last several x 10$^6$ yr in Taurus (Kenyon et al. 1994), the time scale of MC 27 is estimated to be ~10$^4$ yr from the statistics; the number of YSOs younger than 10$^6$ yr is estimated to be ~100 (Kenyon, Hartmann 1995). The upper limit for the luminosity, ~0.1 L$^\odot$ (Kenyon, Hartmann 1995), can be used to further constrain the evolutionary stage. We shall assume a steady mass-accretion rate given by $M = 0.975 c^3/\pi G$ (Shu 1977), where $c_s$ is the effective sound speed, 2 x 10$^{-6}$ M$^\odot$ yr$^{-1}$ for 10 K molecular gas. The accretion luminosity is calculated as $L_{\text{acc}} = G M + M/R^*$, where $M^*$ is the stellar mass and $R^*$ is the stellar radius. The luminosity being <0.1 L$^\odot$ implies a stellar mass of <0.01 M$^\odot$ if we adopt a stellar radius of 1.5 $R^\odot$ from the numerical simulation by Stahler (1988) for stellar mass of <0.3 Afe. The age of a 0.01 M$^\odot$ protostar under a constant mass-accretion rate is then calculated to be ~10$^4$ yr, consistent with that of MC 27 derived above. Therefore, even if MC 27 has formed a star in it, the star must be younger than ~10$^4$ yr. Such a low-luminosity protostellar object in the early stage of star formation has been studied in previous theoretical work (e.g., Boss, Yorke 1995). According to Boss and Yorke (1995), a luminosity <0.1 L$^\odot$ corresponds to a stage younger than ~2 x 10$^4$ yr, which they call Class I. At this stage, the first protostellar core consisting of molecular hydrogen may have been formed or, alternatively, the second (final) protostellar core may have just formed.

More detailed constraints on the evolutionary stage of MC 27 may be obtained through model fitting of the line profiles. First, we show a comparison of the in-
fall motion with the existing theoretical models. One of the most fundamental models is inside-out collapse (Shu 1977); another is run-away collapse (e.g., Larson 1969; Penston 1969). These two models have been well studied theoretically to describe the collapsing process of a dense condensation. Our result needs an infall velocity of 0.2-0.3 km s^{-1} at 2000-3000 AU in order to reproduce the asymmetric absorption profiles. When the infall velocity reaches that value at 2000-3000 AU in inside-out collapse, the infall velocity at 1000 AU must exceed at least 0.5 km s^{-1} (figure 4), which is inconsistent with the present result. When the infall velocity at 1000 AU is below 0.3 km s^{-1}, the velocity at 2000-3000 AU of the inside-out collapse model is too small. In the run-away collapse model of Larson (1969) and Penston (1969), the model cloud has an infinite size, an infall velocity of ~0.6 km s^{-1}, and large mass-infall rates of 5 \times 10^{-5} to 1 \times 10^{-4} M\odot yr^{-1}, which are not consistent with the present values, either. However, the existence of infall motion at 2000-3000 AU indicates that the dynamical motion should exist even before the formation of a protostellar core, because the age of MC 27 is estimated to be quite young, < 10^4 yr. Recent numerical simulations of dynamical collapse with a finite boundary show a similar velocity distribution to the present results, as shown in figure 4 (e.g., Masunaga et al. 1998).

In order to obtain deeper insight, we briefly discuss the physical processes in the collapse. A pre-stellar molecular condensation can be divided into two regimes: one is a magnetically subcritical condensation which is supported from gravitational contraction by magnetic fields; the other is a magnetically supercritical one which is dominated by gravity. Subcritical condensation requires some dissipation mechanism of magnetic fields to contract. Ambipolar diffusion provides a dissipation mechanism, leading to the contraction of subcritical condensations through a relative drift of the charged particles and neutral species in the gas (Nakano 1979; Shu et al. 1987; Lizano, Shu 1989). When the supporting force is reduced to that which is comparable to the gravitational force, dynamical collapse starts. The index of the density distribution of such a dynamically collapsing cloud is estimated to be ~2 (Lizano, Shu 1989), which is consistent with that of MC 27. A supercritical condensation should contract dynamically on nearly the free-fall time scale. The contraction can be described by isothermal self-similar solutions, also having an index of density distribution of ~ -2 (Larson 1969; Penston 1969). In both cases, after the final protostellar core is formed, inside-out collapse occurs.

Infall motion has been recently claimed for another starless condensation in L1544 based on asymmetric self-absorbed profiles (Tafalla et al. 1998). The molecular gas of L1544 is spatially more extended than that of MC 27. The index of the density profile of L1544 has been derived to be ~ -1.5 and the spatial distribution of the L1544 molecular cloud is not circularly symmetric, especially in the J = 1-0 line of C^{18}O (Tafalla et al. 1998). The spherically asymmetric distribution of the molecular gas in L1544 makes any discussion of infall inconclusive, since the self-absorption feature is easily affected by the distribution of the surrounding low-density gas. Molecular line observations with higher-J transitions are necessary to estimate a density higher than ~ 10^4 cm^{-3}, as discussed above, while such information is not available for L1544. These additional observations should reveal the evolutionary status of L1544 more precisely.

We next discuss the wing feature of the HCO^{+} J = 3-2. These wings are localized toward the center of MC 27, at <, 1500 AU. The model fitting discussed above indicates that the origin is probably due to outflow. The estimated dynamical time scale for the wings is ~ 10^6 yr or smaller, which is consistent with that of MC 27. If the wing feature is really due to outflow, this result indicates that the outflow phenomenon occurs at a very early stage of protostellar collapse. Recent theoretical calculations (e.g., Kudoh, Shibata 1997) indeed show that outflow can begin at a very early stage of dynamical collapse after a rotating disk is formed, and that the velocity of the protostellar jet is estimated to be around the Keplerian velocity. If a protostellar core of 0.01 M\odot is already formed in MC 27, the inner gas can have a Keplerian velocity of > 10 km s^{-1} at the inner edge of the disk, which can be a cause of the outflow. High-resolution interferometric observations in higher-J transitions can be used to probe the inner structure of MC 27, thus allowing us to study the origin and onset of the outflow.

Finally, we describe future studies needed to understand the process of dynamical collapse in more detail. While the general properties of dynamical collapse in a very early stage of star formation have been revealed for MC 27, a detailed study on the density distribution and velocity distribution of the inner region of < 1000 AU is necessary. Such a study should reveal the evolutionary stage of MC 27 more precisely, and can be compared with the theory of formation of the first protostellar core. The gas distribution may also reveal when the spherical symmetry breaks to form a disk. More sensitive far-infrared and submillimeter continuum observations make it possible to check whether the protostellar core really exists. The existence of the protostar can easily accelerate the outflow. Moreover, the detection of other objects like MC 27 is important to study the process of dynamical collapse. More surveys of dense molecular condensations are needed for the other star-forming regions, such as Ophiuchus, Chamaeleon, and Lupus, since the number of objects like MC 27 is only ~ 1/100 of the young stars of age ~ 10^6 yr because of its very short time scale of ~ 10^4 yr. With these further studies, we can obtain a better comprehensive knowledge of the most basic prob-
lem, how a protostar is formed via contraction of molecular gas.

We thank S. Inutsuka and H. Masunaga for fruitful discussion on the many aspects of the theoretical study; A. Kawamura for data reduction, discussion, and reading of the manuscript; K. Tachihara for helping observations and reading of the manuscript; and Y. Yonekura for reading the manuscript. We also thank the staff of the CSO for their invaluable assistance. The research of T. O. is supported by the Research Fellowships of the Japan Society for the Promotion of Science.

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