WARM EXTENDED DENSE GAS AT THE HEART OF A COLD COLLAPSING DENSE CORE

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Received 2009 August 18; accepted 2009 October 2; published 2009 November 12

ABSTRACT

In order to investigate when and how the birth of a protostellar core occurs, we made survey observations of four well-studied dense cores in the Taurus molecular cloud using CO transitions in submillimeter bands. We report here the detection of unexpectedly warm (~30–70 K), extended (radius of ~2400 AU), dense (a few times 10^2 cm^{-3}) gas at the heart of one of the dense cores, L1521F (MC27), within the cold dynamically collapsing components. We argue that the detected warm, dense gas may originate from shock regions caused by collisions between the dynamically collapsing components and outflowing/rotating components within the dense core. We propose a new stage of star formation, “warm-in-cold core stage (WICCS),” i.e., the cold collapsing envelope encases the warm extended dense gas at the center due to the formation of a protostellar core. WICCS would constitute a missing link in evolution between a cold quiescent starless core and a young protostar in class 0 stage that has a large-scale bipolar outflow.

Key words: ISM: clouds – ISM: individual (L1521F, MC27) – stars: formation – stars: pre-main sequence – submillimeter

1. INTRODUCTION

Low-mass stars form through gravitational contraction within cold dense condensations, called dark cloud dense cores. The dense cores remain roughly isothermal as long as radiative cooling is comparable to the heating from compression of the medium. This compression is due to the gravitational contraction over ~10^5 years (e.g., Masunaga et al. 1998). When the central density reaches 10^{10}–10^{11} cm^{-3}, compression heating becomes dominant and a condensed, more or less star-sized object, protostellar core, forms at the heart of a dense core (Boss & Yorke 1995; Masunaga et al. 1998).

A starless dense core is a cold (~10 K) dense (>=10^4 cm^{-3}) large (~20,000 AU) condensation of gas and dust (e.g., Bergin & Tafalla 2007). It does not harbor any embedded infrared point source (hereafter IPS). Some evolved starless cores have dynamically collapsing envelopes. On the other hand, class 0 objects (e.g., André et al. 2000), which are embedded in protostellar dense cores with a temperature of ~30 K, a density of >=10^5 cm^{-3}, and a size of <=10,000 AU, are characterized by the existence of IPSs and large-scale molecular bipolar outflows driven by protostars. Note that there are dense cores that harbor very low luminosity embedded sources within them but do not have large-scale bipolar outflows. These objects were used to be categorized as starless cores, however, embedded sources were revealed by deep water maser emission survey at the Nobeyama 45 m telescope (e.g., Furuya et al. 2001) and deep infrared observations by the Spitzer Space Telescope (e.g., Dunham et al. 2008). They are in a stage more evolved than the starless core stage and younger than the class 0 stage. The formation of the protostellar cores must occur in such a transition stage.

In order to investigate when and how the birth of a protostellar core occurs, we observed four dense cores in the Taurus molecular cloud using two CO lines in submillimeter bands, i.e., J = 6–5 (wavelength $\lambda$ 433.544 $\mu$m) and 7–6 (wavelength 371.650 $\mu$m) transitions. The energy levels at J = 5 and J = 6 correspond to 83 K and 116 K, respectively. The critical densities at the temperatures of 100 K traced by the molecule are several times 10^5 cm^{-3}. With the molecular lines that trace both warm and dense gas components, one can study the physical properties of the regions closely related to the final processes of protostellar core formation when material at the center starts warming up due to the formation of the protostellar core.

2. SOURCE SELECTION

Our surveyed dense cores include L1521E, L1498, L1521F, and L1544. These cores are selected because (1) they are well studied and known as objects in early stages of star formation, i.e., the starless core stage or the stage of a dense core that harbors a very low luminosity IPS and does not show a large-scale bipolar outflow, and (2) they are reasonably isolated hence good targets to study internal star formation processes without any external disturbance. Among the aforementioned dense cores, L1521E is in the youngest evolutionary stage because of its richness in carbon-chain molecules (e.g., Hirota 2002). All the cores except for L1521E show a gas infall signature (Hirota et al. 2002; Tafalla et al. 1998, 2004; Onishi et al. 1999). L1498 has a relatively low density of 10^2 cm^{-3} and is in a younger evolutionary stage as compared to L1544 and L1521F. L1521F (Mizuno et al. 1994; Codella et al. 1997; Onishi et al. 1999; Shinnaga et al. 2004; Crapsi et al. 2004) has been one of the primary targets among dense cores because of the short dynamical timescale due to the high density of 10^9 cm^{-3} at the center (Onishi et al. 1999), chemically evolved features (Shinnaga et al. 2004; Crapsi et al. 2004), and the discovery of the IPS, L1521F-IRS, which may be a protostar in the making, within the dense core using the Spitzer Space Telescope (Terebey et al. 2005, 2009; Bourke et al. 2006). L1544 shows a similar nature to L1521F, however, no IPS has been detected to date.
Based on the observed properties, L1521F is the most evolved sample in the set.

For L1521F, the Spitzer observation imaged a bipolar nebula of scattered light extending in the east–west direction associated with L1521F-IRS (Bourke et al. 2006; Terebey et al. 2009), which may trace a cavity. However, no large-scale bipolar outflow is observed using spectroscopy. A deep centimeter continuum observation confirms that there are no shock-ionized inner regions of a bipolar outflow from a \(~0.1\ L_\odot\) source (Harvey et al. 2002). L1521F-IRS is not categorized as a class 0 source owing to the lack of a large-scale bipolar outflow. It is in an evolutionary category similar to GF 9-2 (e.g., Furuya et al. 2006, 2009) that shows very weak water maser emission from an embedded source and does not have a large-scale bipolar outflow.

3. OBSERVATIONS

The CO observations in submillimeter bands were carried out at the Caltech Submillimeter Observatory (CSO). The CO \(J = 6 \rightarrow 5\) (frequency \(\nu = 691.473076\ GHz\); Goldsmith et al. 1981) and \(7 \rightarrow 6\) (\(\nu = 806.651801\ GHz\); Schultz et al. 1985) data were taken on 2006 February 6–8 and on 2009 January 22 UT, respectively. The high-altitude dry site, sensitive receivers, and high efficiency of the telescope combined to permit the observations. The Dish Surface Optimization System was used during the observations to compensate for the gravitational deformation of the 10.4 m diameter reflector (Leong 2005). The telescope’s pointing was checked every 1–2 hr using planets. The pointing accuracy is estimated to be \(\sim 3''\) for both observations, and the accuracy of the map registration of the two CO transitions is within \(3''\).

Cryogenically cooled SIS receivers operation at 4 K at the CSO that we used for the observations produced typical single sideband system temperature of \(\sim 3900\ K\) at 433.5 \(\mu\)m and \(\sim 2300–3000\ K\) at 371.7 \(\mu\)m (Kooi et al. 2000) measured with a 50 MHz bandwidth spectrometer. The beam chopping method was used. The beam sizes at the two wavelengths are about \(10''\) and \(9''\) at 433.5 and 371.7 \(\mu\)m, respectively. From observations of Mars and Saturn, the main beam efficiencies are measured to be \(\sim 30\%\) and \(\sim 35\%\) at 433.5 \(\mu\)m and 371.7 \(\mu\)m at elevations of \(30''\) and \(48''\), respectively. The rms noise levels for both observations are about 0.6–1.4 \(K\) in \(T_{\text{mb}}\). The velocity resolution of both observations is \(\sim 0.02\ km\ s^{-1}\).

4. RESULTS

Among the observed dense cores, only one, L1521F, shows significant CO line emission at both transitions (Figure 1). The rest of the dense cores do not show the CO \(6 \rightarrow 5\) line emission brighter than 0.3 K in the observed main beam temperatures \(T_{\text{mb}}\). Observed properties of CO lines of L1521F are summarized in Table 1. \(T_{\text{mb}}\) values of the CO transitions are weak (see Table 1), suggesting that the emission may be optically thin. The peak \(T_{\text{mb}}\) is observed at the position of R.A. = \(4^h25^m43^s.29\), decl. = \(26^\circ45'8.7''\) (B1950.0) for both transitions. Note that L1521F-IRS is located at \(9''\) south of the peak position. Considering the thermal velocity width of the CO gas at 100 K is only about 0.5 km s\(^{-1}\), a significant fraction of the broad velocity widths originates from non-thermal motions.

We estimate the temperature of the observed warm dense gas components. Taking advantage of the similar beam sizes of the observations of the two transitions, one can derive the excitation temperature \(T_{\text{ex}}\) using the following equation (e.g., Shinnaga et al. 2008):

\[
T_{\text{ex}} = \frac{38.714 \ K}{\ln \left[ \left( \frac{\nu}{J} \right)^2 \frac{T_{\text{mb}}(\text{CO} J \rightarrow J-1)}{T_{\text{mb}}(\text{CO} J \rightarrow J-2)} \right]}
\]

\(T_{\text{ex}}\) values estimated at the positions of (R.A. offset, decl. offset) = \((0'', 0'')\), \((-10'', +10'')\), \((-10'', 0'')\), and \((-10'', -10'')\) are \(57 \pm 1.7\), \(40 \pm 7.4\), and \(68 \pm 5.5\) K, respectively. Note that the CO \(7 \rightarrow 6\) emission is not detected toward the position of L1521F-IRS, indicating that the temperature near the IPS is still low \((\lesssim 30\) K). Over the central \(30'' \times 30''\) region (corresponds to 4200 AU), the averaged \(T_{\text{ex}}\) is calculated to be 34.4 \pm 0.94 K. These temperatures are much higher than the \(T_{\text{ex}}\) measured with an \(N_2H^+\) transition, 5.0 K (Shinnaga et al. 2004).

Figure 2 presents the total integrated intensity map of the CO \(J = 6 \rightarrow 5\) emission that traces the warm extended dense gas (hereafter WEDG), overlaid on the dust continuum map at 850 \(\mu\)m that traces the cold \((-10\) K\) extended (16,000 AU) dense \((\gtrsim 10^5\ cm^{-3})\) condensation (Shinnaga et al. 2004). The observed effective radius of WEDG within the 3\(\sigma\) contour is...
The observed positions. The beam sizes of the CO $6\rightarrow 5$ transition are not found toward the position of the IPS. Infrared pumping is ruled out due to the large vibrational level spacing of CO ($\sim 3000$ K; Carroll & Goldsmith 1981). The protostellar core’s temperature does not become higher than $3000$ K as molecular hydrogen begins to dissociate at $\approx 2400$ K. It is implausible that UV radiation from the accretion disk heats the observed CO gas as the peak $T_{mb}$ values of both transitions are not found toward the position of the IPS.

On the other hand, shocks would be able to pump the gas up to $\sim 100$ K over a large region (Neufeld et al. 1995). In fact, a systematic velocity pattern is not measured in WEDG, indicating that WEDG may be excited in shock-heated regions generated by the collision between the cold dynamically collapsing components and outflowing/rotating components near the center. Considering the presence of L1521F-IRS, it is highly likely that some outflow activities have already been initiated.

The cavity of the bipolar nebula also indicates the existence of a small jet associated with the protostar. Furthermore, L1521F-IRS may have a large rotating circumstellar disk with a size of the order of $10^3$ AU. The north–south elongated feature seen in the $850$ $\mu$m dust continuum map may indicate the existence of the north–south elongated disk that is perpendicular to the cavity axis, i.e., perpendicular to the axis of the bipolar nebula. Based on the measured velocity gradient of $15$ km s$^{-1}$ pc$^{-1}$ over $0.01$ pc with a clump mass of $0.1$ $M_\odot$ by using the $N_2H^+$ $J = 1 - 0$ transition at the center of the dense core (Shinnaga et al. 2004), the centrifugal radius of the collapsing medium is estimated to be about $10^3$ AU. In addition, the asymmetric distribution of WEDG supports the view that WEDG comes from the shocks but not from the small jet itself. If the two CO lines are in the LTE condition, the lower limit of the mass of WEDG becomes an order of $10^{-2}$ $M_\odot$.

Figure 3 illustrates a magnified view of the center of the dense core that we propose. The cavity with blue color may be in front of the disk, while the cavity with green color is behind the disk, along the line of sight. The cavity in front is opening toward the west from L1521F-IRS, which may channel part of the outflowing gas, making the shock easier to observe on the western side. The north–south extension of WEDG may be due to the circumstellar disk elongated along the north–south direction.

6. SUMMARY AND FUTURE WORK

We made survey observations using the two CO transitions in submillimeter bands to search for the dark cloud dense cores.
which harbor newly born protostellar cores and to investigate
the physical properties of the objects. This study identified
a transient stage of star formation between the starless core
and class 0 stages. As the starless core stage progresses, the
cold collapsing dense material starts warming up at the center
due to the formation of a protostellar core and forms WEDG
in the central region. We name this new stage “warm-in-cold
core stage (WICCS).” One should search for WEDG using
warm and dense gas tracers such as the CO 6−5 and 7−6
transitions to identify the objects in WICCS. This object would
constitute a missing link in evolution between a starless core and
a protostar, yielding an important step toward understanding of
the formation mechanism of a protostellar core and a protostar.
Survey observations of CO transitions in submillimeter bands
toward dense cores in early evolutionary stages are necessary
to add more samples in WICCS in order to obtain a complete
picture of WICCS.

This research was performed at the Caltech Submillimeter
Observatory, supported by NSF grants AST-05-40882 and AST-
0838261. This work was also supported by Grant-in-Aids
from the Ministry of Education, Culture, Sports, Science and
Technology of Japan (No. 19204020 and No. 20740113). H.S.
is grateful to Richard Chamberlin, Brian Force, and Hiroshige
Yoshida for their support on the observations in 2009 January.

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