ASTE SUBMILLIMETER OBSERVATIONS OF A YOUNG STELLAR OBJECT CONDENSATION IN CEDERBLAD 110

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ABSTRACT

We present results of submillimeter observations of a low-mass young stellar object (YSO) condensation in the Cederblad 110 region of the Chamaeleon I dark cloud with the Atacama Submillimeter Telescope Experiment. Our HCO+(J = 4–3) map reveals a dense molecular gas with an extent of ~0.1 pc, which is a complex of two envelopes associated with class I sources Ced 110 IRS 4 and IRS 11 and a very young object Cha-MMS 1. The other two class I sources in this region, IRS 6 and NIR 89, are located outside the clump and have no extended HCO+ emission. HCO+ abundance is calculated to be 2.6 × 10⁻⁶ for MMS 1 and 3.4 × 10⁻⁶ for IRS 4, which are comparable to the reported value for other young sources. Bipolar outflows from IRS 4 and IRS 6 are detected in our 12CO(J = 3–2) map. The outflow from IRS 4 seems to collide with Cha-MMS 1. The outflow has enough momentum to affect gas motion in MMS 1, although no sign has been detected to indicate that a triggered star formation has occurred.

Subject headings: ISM: clouds — ISM: jets and outflows — stars: formation — stars: individual (Ced 110 IRS 4, Cha-MMS 1) — stars: low-mass, brown dwarfs — stars: pre–main-sequence

1. INTRODUCTION

1.1. Single Star Formation and Cluster Formation

A number of past observations and theoretical researches have revealed a rough scenario for the formation of isolated, single low-mass stars. That is, a gravitational collapse of a molecular cloud core is the starting point of star formation, then a protostar (e.g., Takakuwa et al. 2003), and cause outflow-driven star formation (Arce & Goodman 2002), affect the motion of the cloud around the protostar (e.g., Takakwa et al. 2003), and cause outflow-triggered turbulence (Yokogawa et al. 2003), as well as generate turbulence and limit the efficiency of star formation (Nakano et al. 1995; Matzner & McKee 2000).

It is still veiled how to form stars in a group or a cluster (Lada & Lada 2003), although most stars are known to be born that way. If stars are forming in a group or cluster, impacts of outflows on the environment may be greater than in the formation of isolated stars. Therefore, it is important to study interactions between outflows and dense gas in cluster-forming regions for comprehensive understandings of star formation processes.

1.2. Cederblad 110 Region

The Cederblad (Ced) 110 region (Cederblad 1946) is located in the center of the Chamaeleon (Cha) I dark cloud, one of the low-mass star formation regions in the solar vicinity (D = 160 pc; Whittet et al. 1997). Haikala et al. (2005) identified a C18O clump in the Ced 110 region, whose radius is 0.19 pc and mass is 11.7 M☉. This is the most massive clump in their samples. Infrared and millimeter continuum observations (Prusti et al. 1991; Reipurth et al. 1996; Zinnecker et al. 1999; Lehtinen et al. 2001; Persi et al. 2001) have revealed that seven YSOs at different evolutionary stages and one very young source are clustered within ~0.2 pc. In Table 1 we list the objects with their position, IR class, Tbol (Myers & Ladd 1993), and Lbol.

The youngest object in this region, Cha-MMS 1, was detected by 1.3 mm continuum observations by Reipurth et al. (1996). At this position, Lehtinen et al. (2001) identified the far-IR object Ced 110 IRS 10 by observations with the Infrared Space Observatory (ISO), while no corresponding source has been detected with near-IR observations. Thus, MMS 1 is considered to be a “real protostar” (Lehtinen et al. 2001). However, Lehtinen et al. (2003) could not detect 3 or 6 cm radio continuum emission. This result indicates MMS 1 does not have any jets or outflows. They noted that MMS 1 is still at a prestellar stage.

Ced 110 IRS 4, a class I object, is associated with a reflection nebula that is extended in a north–south direction and is divided by a thick edge-on dust disk (Zinnecker et al. 1999; Persi et al. 2001). Henning et al. (1993) detected a 1.3 mm radio continuum emission from this object, while extended emission was not detected (Reipurth et al. 1996).

Molecular outflow was detected in this region by 12CO(J = 1–0) observations with the Swedish-ESO Submillimeter Telescope (SEST; Mattila et al. 1989; Prusti et al. 1991), but the identification of its driving source has been controversial. Originally, IRS 4 was thought to be driving this outflow. However, Reipurth et al. (1996) detected MMS 1 and suggested that MMS 1 is the driving source of the outflow as well as the nearby Herbig-Haro (HH) objects HH 49/50 (see also Kontinen et al. 2000). While Lehtinen et al. (2003) revealed that MMS 1 is associated with no jets, Bally et al. (2006) suggested that a parsec-scale outflow is ejected from MMS 1 based on the positional relationship among the HH objects and the YSOs in their large-area shock survey. Lack of high-resolution mapping observations of the outflow (e.g., the mapping grid was 1' in Mattila et al. [1989]) have made it difficult to resolve this issue.
Ced 110 IRS 11 was first detected by Zinnecker et al. (1999) as IRS 4E in their near-IR image. Lehtinen et al. (2001) tentatively detected a far-IR source from ISO data and identified IRS 11 as ISO-Cha 86 (Persi et al. 2000). The coordinates for IRS 11 in Table 1 are based on the position for Cha 86 in Persi et al. (2001).

In this paper we focus on the following three points: (1) the distribution of dense gas in the YSO clustering region, (2) the influence of outflows from older protostars on newer ones and the surrounding gas, and (3) the “blue asymmetry” line profile toward YSOs, which indicates the existence of infalling gas (Leung & Brown 1977; Zhou 1992). To investigate them we observed the HCO0 line along the line from IRS 4 to MMS 1. The CH3OH line was observed along the line from IRS 4 to MMS 1. The CO(J = 3–2) and HCO+ (J = 4–3) lines are easier to detect than those of other lines, we made the rms noise level go down to 0.05 K for other lines, their typical rms noise was 0.3 and 0.15 K, respectively. We made additional integration toward the YSOs for improving signal-to-noise ratio in the HCO+ line, reaching a rms noise of 0.1 K. For other lines, we made the rms noise level go down to 0.05 K for H13CO+, 0.1 K for CH3OH, 0.15 K for SiO, and 0.2 K for SO. Despite a careful inspection, no emissions from shock-tracing lines were found. The observed point for the shock-tracer molecules are indicated on Figure 1.

We observed H13CO+ lines toward Ced 110 IRS 4 and Cha-MMS 1. The CH3OH line was observed along the line from IRS 4 to MMS 1 with 200 km s−1 spatial resolution. SO and SiO lines were observed simultaneously in opposite sides toward the Kontinen et al. (2000) SO northern peak, (α, δ)(J2000.0) = (11h56m26s, −76°57′39″) and (11h54m20s, −78°03′44″). These positions were checked to be free of emission.

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The telescope pointing was regularly checked by observing Jupiter, Saturn, or IRC +10216 every 1 or 2 hr during observations, and the error was estimated to be about 5" peak to peak. Intensity calibration was carried out by the chopper-wheel method (Kutner & Ulich 1981). The absolute intensity is calibrated by assuming that $T_{\text{mb}}$ of IRC +10216 for CO($J = 3 \rightarrow 2$) is 32.5 K (Wang et al. 1994). The daily variability was checked by observing L1551 IRS 5 for HCO$^+$ and by observing Ori KL for H$^{13}$CO$^+$, CH$_3$OH, SO, and SiO. The sideband ratio was assumed to be unity. The zenith 220 GHz opacity varied from $\tau \sim 0.05$ to $\sim 0.1$. Matsuo et al. (1998) reported the atmospheric transmission is marginally resolved with the viewpoint of line width, that is, the dip in the HCO$^+$ line profiles obtained at YSO positions are shown in Figure 7. The CO line profile from ambient gas is sampled at the boundary of the map in Figure 7a, and the extension of the clump with a position angle $0^\circ$ corresponds well to the 200 $\mu$m ridge emission observed with ISO (Lehtinen et al. 2001).

### 3. RESULTS

#### 3.1. Overview

Figures 1 and 2 show the observed maps of the CO($J = 3 \rightarrow 2$) emission. The CO($J = 3 \rightarrow 2$) emission was detected at all points within the $4' \times 3'$ map with a varying degree of intensity. While IRS 4 and IRS 6, we detected CO high-velocity components most probably caused by outflows. The details of the outflows are described in §§3.3 and 4.3.

Figure 3 shows the integrated intensity map of the HCO$^+$(J = 4 $\leftarrow 3$) line in the velocity range of 2.0 km s$^{-1} \leq V_{\text{LSR}} \leq 7.0$ km s$^{-1}$. A HCO$^+$ clump of dense gas is seen in Figure 3. This clump is an aggregate of three independent envelopes associated with Ced 110 IRS 4, IRS 11, and Cha-MMS 1. The envelope associated with IRS 11 seems to be apart from the component associated with IRS 4 in the $V_{\text{LSR}} = 4.78$ and 5.00 km s$^{-1}$ panels of Figure 4. MMS 1 is also distinguishable in the $V_{\text{LSR}} = 3.92$ and 4.13 km s$^{-1}$ panels. Figures 5 and 6 are the position-velocity diagrams of CO and HCO$^+$ lines along lines a and b in Figure 3, respectively. In Figure 5 the components associated with IRS 4 and IRS 11 are marginally resolved with the viewpoint of line width, that is, the emission associated with IRS 4 exhibits a distinctly larger line width than that for IRS 11. The HCO$^+$ clump covers $140'' \times 110''$ (0.11 pc $\times$ 0.085 pc) above the 3 $\sigma$ noise level. The extension of the clump with a position angle $\sim 45^\circ$ corresponds well to the 200 $\mu$m ridge emission observed with ISO (Lehtinen et al. 2001).

#### 3.2. CO and HCO$^+$ Line Profiles

The CO($J = 3 \rightarrow 2$), HCO$^+$(J = 4 $\leftarrow 3$), and H$^{13}$CO$^+$(J = 4 $\leftarrow 3$) line profiles obtained at YSO positions are shown in Figure 7. The CO line profile from ambient gas is sampled at the boundary of the map and shown in Figure 7a by a dotted line. Almost all CO line profiles have a dip at $V_{\text{LSR}} \sim 4.3$ km s$^{-1}$. The dip also appears in some HCO$^+$ line profiles at the same velocity. The velocity of the dip is identical to that of C$^{18}$O clump number 3 identified in the Ced 110 region by Haikala et al. (2005) and also gives close agreement with the velocities of optically thin lines observed by Kontinen et al. (2000). These correspondences mean that this dip is caused by self-absorption by less excited gas, not the result of two emission components with different velocities along the same line of sight. Since the observed region corresponds to one C$^{18}$O clump, the outer gas of the clump in the lower excitation level would make the CO absorption. The dip in the HCO$^+$(J = 4 $\leftarrow 3$) line indicates a significant population of the J = 3 level that requires a moderately high density, but with a lower J = 4 $\leftarrow 3$ excitation temperature than in the center of the clump. This is a reflection of the density gradient in the clump. We can find these dips in Figures 5 and 6. This dip prevents the channel map (Fig. 4) from representing the actual distribution of interstellar matter in the dip velocity. The indentations of contours located at the south of IRS4 and a lack of a peak around MMS 1 in the panels of $V_{\text{LSR}} = 4.35$ and 4.57 km s$^{-1}$ of Figure 4 may be due to the self-absorption. It is conceivable that other reasons such as depletion and chemistry in the dense gas cause this lack of a peak. The issue of molecular depletion is discussed in §4.1.

The parameters of the lines detected at YSO positions are summarized in Tables 2, 3, and 4. We fitted the spectral data of HCO$^+$ and H$^{13}$CO$^+$ with a Gaussian profile. The error estimates of the values in the tables come from the fit. In deriving the line parameters, the velocity ranges of outflows and self-absorption features in the lines are eliminated in the fitting processes. Although this may have some defectiveness, this is the optimal handling of our data.

#### 3.3. Individual Sources

##### 3.3.1. Ced 110 IRS 4 and the Outflow

Bipolar outflow from IRS 4 is detected in our CO(J = 3 $\leftarrow 2$) observations. This outflow had been also detected by Mattila et al. (1989) and Prusti et al. (1991) with their CO(J = 1 $\leftarrow 0$) observations. We compared the line profiles toward IRS 4 with that of the ambient gas obtained at the edge of the map in $(\alpha, \delta) = (2000.0, (11^h 06^m 24.3^s, -77^\circ 21' 16.7''))$. Judging from this comparison shown in Figure 7a, the line profile in the velocity ranges of $V_{\text{LSR}} \leq 3.0$ km s$^{-1}$ and $V_{\text{LSR}} \geq 6.3$ km s$^{-1}$ are not affected by the ambient gas, and thus, we identified these ranges as outflow components.
The distribution of the outflow components from IRS 4 are shown in Figures 1 (integrated intensity map) and 2 (channel map). The blueshifted and redshifted outflows show a different aspect. The spatial extent of the blueshifted outflow is considerably larger than that of the redshifted outflow. Furthermore, the highest velocity component of the blueshifted outflow lies midway between IRS 4 and MMS 1, while the velocity reaches its peak around IRS 4 in the redshifted flow. The near-IR images (Zinnecker et al. 1999; Persi et al. 2001) indicate that IRS 4 is seen nearly edge-on. The observed distribution of the blueshifted component of the outflow extending to the south suggests that the outflow axis slightly inclines with the southern side closer than the northern side. This configuration is in agreement with the previous remarks on the inclination of IRS 4 based on the color gradient of the nebulae (Zinnecker et al. 1999). They found that the northern part of the reflection nebula is redder than the southern part, which suggests that the northern part is tilted away from us. Our integrated intensity map (Fig. 1) does not show the redshifted component in the south of MMS 1 reported in the literature (Mattila et al. 1989; Prusti et al. 1991). In the channel map (Fig. 2), however, one can see the extended redshifted emission at \( V_{\text{LSR}} = 6.52 \text{ km s}^{-1} \), and this could be its counterpart.

Observations of the \(^{13}\text{CO}\) \((J = 4-3)\) line were also performed toward IRS 4 (Fig. 7a) with a 43 mK noise level. The FWHM of this line, \( \Delta V = 1.72 \pm 0.29 \text{ km s}^{-1} \), corresponds to that of the HCO\(^+\) line within the margin of error. This supports the detection of the line. With this result, we discuss molecular abundance in § 4.1.

### 3.3.2. Cha-MMS1

In Figure 7b we show the CO, HCO\(^+\), and \(^{13}\text{CO}\) line profiles toward Cha-MMS 1. The dip in the HCO\(^+\) line is deeper than that of IRS 4. This deeper dip shows that MMS 1 is deeply embedded in the densest part of \(^{18}\text{O}\) clump number 3 (Haikala et al. 2005), because MMS 1 lies nearer to the position of the peak intensity of \(^{18}\text{O}\) than IRS 4.

We calculated the HCO\(^+\) “original” integrated intensity with a Gaussian fit using the line profiles in the velocity ranges which
4 DISCUSSION

4.1 Molecular Abundance in Envelopes

In dense, cold gas envelopes of protostars and prestellar cores, molecules often freeze out onto dust grains (see, e.g., Jørgensen et al. 2005). On the other hand, the abundance of some species like HCO⁺ are known to be enhanced in outflows (Rawlings et al. 2004).

We examined the abundance of HCO⁺ toward MMS 1 and IRS 4 by means of our H13CO⁺ (J = 4−3) observations and 1.3 mm continuum observations (Henning et al. 1993; Reipurth et al. 1996). Assuming that the dust emission is optically thin, the column density of the H₂ molecule, \( N(H_2) \), is calculated with

\[
N(H_2) = \frac{S_\nu^{\text{beam}}}{\Omega_{\text{beam}} \mu m_1 \kappa_{1.3} B_\nu(T_d)};
\]

where \( S_\nu^{\text{beam}} \) is the 1.3 mm flux density per beam, \( \Omega_{\text{beam}} \) is the beam solid angle, \( \mu = 2.3 \) is the mean molecular weight, \( m_1 \) is the mass of the H atom, \( \kappa_{1.3} \) is the mass absorption coefficient per gram, and \( B_\nu(T_d) \) is the Planck function at the dust temperature \( T_d \). We employed \( \kappa_{1.3} = 0.01 \text{ cm}^2 \text{ g}^{-1} \) for IRS 4, which is the recommended value for very dense regions (Ossenkopf...
Meanwhile, we applied the value of 0.005 cm$^2$ g$^{-1}$ for MMS 1, which is the adopted value for pre-stellar core L1689B (Andrè et al. 1996). The substituted values of $S_{\nu,\text{beam}}$ are 370 mJy for MMS 1 (Reipurth et al. 1996) and 101 mJy for IRS 4 (Henning et al. 1993). We employed a dust temperature of 20 and 21 K for MMS 1 and IRS 4, respectively, based on Lehtinen et al. (2001). The resulting H$_2$ column density is $2.2 \times 10^{23}$ cm$^{-2}$ for MMS 1 and $2.8 \times 10^{22}$ cm$^{-2}$ for IRS 4.

We also calculated the column density of H$^{13}$CO$^+$ under LTE conditions and the assumption that the excitation temperature equals the dust temperature. Comparing $N$(H$_2$) obtained from dust observations with $N$(H$^{13}$CO$^+$), we estimated the abundance of HCO$^+$ to be $X$(HCO$^+$) = $2.6 \times 10^{-10}$ for MMS 1 and $3.4 \times 10^{-9}$ for IRS 4. We set the isotropy ratio of [H$^{13}$CO$^+$/HCO$^+$] = 70. The results are summarized in Table 5.

Jørgensen et al. (2004) reported average $X$(HCO$^+$) = $8.0 \times 10^{-10}$ for pre-stellar cores and $1.1 \times 10^{-8}$ for Class I sources. Jørgensen et al. (2005) pointed out that the molecular depletion in envelopes of Class I objects is less significant because of heating by their central sources. Furthermore, Rawlings et al. (2004) reported that the abundance of HCO$^+$ is enhanced in molecular outflows. Our results are not in contradiction with abundances reported in similar objects. However, it is not appropriate to investigate the results in more detail, because the mass absorption...
and HCO+(J = 4–3) are shown with thin and thick lines, respectively. The first contour level and contour interval are 1.5 K for CO and 0.9 K for HCO+. The positions of IRS 4, IRS 6, and IRS 11 are indicated with dashed lines.

The other problem is optical depth. Choosing molecular lines with appropriate optical depth is necessary to detect infall motion toward protostars (Leung & Brown 1977; Zhou 1992). In a simplified model of an infalling envelope, the blueshifted line component is stronger than the redshifted component. This is because the redshifted component is absorbed by the cooler infalling material in the near half of the envelope along the line of sight. Do our results mean these objects have no infalling gas?

Some reasons are suggested why blue asymmetry does not appear in all sources. One great problem is confusion with outflows. If a redshifted outflow exists in the telescope beam, the redshifted line components absorbed by the infalling envelope would be compensated. It is also difficult to separate the influence of other velocity components such as circumstellar disks and ambient gas in observations with a large beam of single dish radio telescopes. In our observations, as an example, a wing component is detected in the CO line profile toward IRS 4. This profile obviously shows that our 22m beam covers the outflowing component. In general, there are some possibilities to confuse not only outflow, but core rotation and other large-scale physical structures with infall, all of which affect obtained line profiles. Thus, it is difficult to investigate infall motion in targeted observations toward protostars without high-resolution spatial information about the envelope.

The other problem is optical depth. Choosing molecular lines with appropriate optical depth is necessary to detect infall motion of the inner portion of the envelope in general, not only for Ced 110. When a protostar is highly embedded in a dense clump and an observed line becomes optically too thick, the line cannot convey information of the inner infalling region any more and reflects only properties of foreground components.

4.3. Kinematics of Outflows

We calculated the physical parameters of the outflows from IRS4 according to the procedures of Choi et al. (1993). In these procedures, the CO column density for each channel in units of cm\(^{-2}\), \(N_{i}^{CO}\), and the mass per channel, \(M_{i}\), are calculated from

\[
N_{i}^{CO} = 1.10 \times 10^{15} \frac{T_{R3-2} \Delta V}{D(n, T_{K})} \exp(-\tau_{32}), \tag{2}
\]

\[
M_{i} = \mu m_{H_{2}} d^{2} \Omega \bar{N}_{i}^{CO} \frac{[H]}{[C]} \frac{[C]}{[CO]}, \tag{3}
\]

where

\[
D(n, T_{K}) = f_{2} \left[ J_{v}(T_{ex}) - J_{v}(T_{bk}) \right] (1 - \exp(-16.597/T_{ex})), \tag{4}
\]

\(T_{R3-2}\) is the line intensity of the CO(J = 3–2) line, \(\Delta V\) is the channel width in km s\(^{-1}\), \(f_{2}\) is the fraction of CO molecules in the J = 2 state, \(d = 160\) pc is the distance to the Cha I cloud, \(\Omega\) is the solid angle subtended by emission, \([H]/[C] = 2.5 \times 10^{3}\), \([C]/[CO] = 8\), and \(\tau_{32}\) is the optical depth of the line. We calculated \(\tau_{32} \sim 0.4\) comparing with CO(J = 3–2) and CO(J = 1–0) line-wing intensity (Prusti et al. 1991). In this calculation, we assumed that the excitation temperatures \(T_{ex}\) of the two lines are equal to 20 K. According to large velocity gradient simulations by Choi et al. (1993), \(D(n, T_{K})\) does not vary so much within the reasonable density and temperature range. Therefore, we set the same value of \(D(n, T_{K}) = 1.5\) as in Choi et al. (1993). The mass \(M\), momentum \(P\), and kinetic energy \(E_{K}\) can be estimated from

\[
M = \Sigma_{i} M_{i}, \tag{5}
\]

\[
P = \Sigma_{i} M_{i} |V_{i} - V_{0}|, \tag{6}
\]

\[
E_{K} = \Sigma_{i} \frac{1}{2} M_{i} (V_{i} - V_{0})^2. \tag{7}
\]
Fig. 7.—HCO$^+$(J = 4–3) (multiplied by a factor of 2), CO(J = 3–2) (with 2 K offset), and H$^{13}$CO$^+$(J = 4–3) (only in IRS 4 and MMS 1 panels with 12 K offset and multiplied by a factor of 15) line profiles toward Cha-MMS 1 and YSOs in Ced 110 region. In panel a, the spectrum toward the edge of the map is indicated with a dotted line, and the borders between outflow and line core are shown with two vertical lines. We identified $V_{LSR} \leq 3.0$ km s$^{-1}$ and $V_{LSR} \geq 6.3$ km s$^{-1}$ as outflow.
where $V_0$ is the system velocity. We also calculated the dynamical timescale $t_{\text{dyn}} = R/V_{\text{ch}}$, where the characteristic velocity $V_{\text{ch}} = P/M$, mass loss rate $\dot{M} = M/t_{\text{dyn}}$, and average driving force $F = P/t_{\text{dyn}}$.

The results are shown in Table 6. We adopted an inclination of the outflow axis from the line of sight of $i = 72^\circ$ (Pontoppidan & Dullemond 2005). They derived this value through comparing near-IR images with three-dimensional Monte Carlo radiative transfer code of a disk-shadow projection model. This value is consistent with the fact that the high-resolution infrared images (Zinnecker et al. 1999; Persi et al. 2001) clearly show the edge-on disklike silhouette of IRS4.

We compared the derived values with those in a statistical study of outflows (Wu et al. 2004) in which they show a correlation between the mass, $\dot{M}_{\text{bol}}$, and $P$ for 391 samples. The mass of IRS 4’s blueshifted outflow is smaller by about 1 order of magnitude than the average of the same $\dot{M}_{\text{bol}}$ sources in Wu et al. (2004), but it is still within the range of variation of the data.

In contrast, the derived mass loss rate is rather large in IRS 4 despite its small size. Generally, the mass loss rate by jets is about 1% and that by outflows is 10% of the mass accretion rate (Hartigan et al. 1995). The derived value of $1.1 \times 10^{-6} M_{\odot} \text{yr}^{-1}$ is comparable to the typical accretion rate for protostars, $10^{-9} M_{\odot} \text{yr}^{-1}$, derived by the similarity solution for thermally supported clouds with 10 K (Hartmann 1998).

HH 49/50 is a group of knots located 10.5’ southwest of the Ced 110 region. Studies of radial velocity and proper motion (Schwartz & Dopita 1980; Schwartz et al. 1984) revealed the knots move toward the southwest and away from us. Mattila et al. (1989) and Prusti et al. (1991) identified Ced 110 IRS 4 as the driving source of these HH objects judging from their CO outflow map, because they found a diffuse redshifted component that extends in the southwest of IRS 4 and the alignment of knots is almost parallel to the direction to IRS 4. In our observations, we detected two components that extend to the south of IRS 4. One is the prominent blueshifted outflow which has an opposite line-of-sight direction of movement from HH objects. The other is the diffuse redshifted component that appeared in Figure 2. This complicated morphology makes it difficult to discuss the relation between IRS 4 and HH 49/50. To resolve this issue, one should enlarge CO observations toward the southwest to know the larger structure of the outflow.

In Figures 5 and 6, the HCO$^+$ line toward IRS 4 indicates a wide profile as well as a CO line. Infalling and outflowing gas seem to be the causes of this wide line (Gregersen et al. 1997; Masunaga & Inutsuka 2000), and perhaps, both the effects are blended. In both position-velocity diagrams, the blueshifted component of the HCO$^+$ line is broader than the redshifted component. This is identical to the tendency of CO outflow, which indicates the wide HCO$^+$ line is mainly caused by the outflow. As in the HCO$^+$ channel map (Fig. 4), the blueshifted component extends to the west of IRS 4, whereas the redshifted component is elongated to the north. This aspect again corresponds with the morphology of the CO outflow (Fig. 2).

Another method to use to determine what makes the wide line profile is to compare the velocity of infalling and outflowing gas. We calculated the free-fall velocity of infalling gas, $v_{\text{ff}} = 0.31–0.56 \text{ km s}^{-1}$, assuming the mass range of $0.10–0.32 M_{\odot}$ derived by Persi et al. (2001) and a diameter of the envelope of $1.7 \times 10^{-2} \text{ pc}$. These $v_{\text{ff}}$ are smaller than the line width, which indicates the outflow has a larger contribution to the line profile.

Toward IRS 6, we derived some physical parameters of the outflow in the same procedure as for IRS 4 and show the result in Table 6. In the case of IRS 6, we could not correct the effect of the inclination of the outflow axis because of a lack of information. Besides, there have been no CO($J = 1–0$) observations toward IRS 6 in previous years, so we could not derive $T_{\text{bol}}$. Here we use the same $T_{\text{bol}}$ as toward IRS 4. Although there are ambiguities of inclination and optical depth, the outflow from IRS 6 is more than 1 order of magnitude smaller than that from IRS 4. This is consistent with our estimation of its evolved status with a small envelope. This interpretation is not consistent with the young age of the outflow; however, when the outflow is nearly in pole-on configuration, the dynamical timescale of the outflow will be calculated.

### Table 2

| Name             | $T_{\text{bol}}$ (K) | $\int T_{\text{bol}}dv$ (K km s$^{-1}$) |
|------------------|----------------------|----------------------------------------|
| Cha MMS 1......  | 1.64 ± 0.09          | 4.49 ± 0.12                            |
| Ced 110 IRS 4... | 3.00 ± 0.09          | 4.46 ± 0.13                            |
| Ced 110 IRS 6... | 0.65 ± 0.09          | 4.62 ± 0.18                            |
| Ced 110 IRS 11.. | 1.47 ± 0.08          | 4.67 ± 0.13                            |
| NIR 89........... | <0.16                | ...                                    |
| ISO-Chal 97...... | <0.17                | ...                                    |
| ISO-Chal 101..... | <0.36                | ...                                    |
| Ced 110 IRS 2... | <0.29                | ...                                    |

### Table 3

| Name             | $V_{\text{LSR}}$ (km s$^{-1}$) | $\Delta V$ (km s$^{-1}$) | $\int T_{\text{bol}}dv$ (K km s$^{-1}$) |
|------------------|--------------------------------|--------------------------|----------------------------------------|
| Cha MMS 1......  | 2.49 ± 0.12                    | 0.68 ± 0.14              | 1.11 ± 0.01                            |
| Ced 110 IRS 4... | 3.00 ± 0.09                    | 1.55 ± 0.15              | 1.58 ± 0.01                            |
| Ced 110 IRS 6... | 1.53 ± 0.28                    | 0.73 ± 0.01              | 1.35 ± 0.01                            |
| Ced 110 IRS 11.. | 0.90 ± 0.15                    | 0.35 ± 0.01              | <0.35                                  |
| NIR 89........... | ...                            | ...                      | <0.35                                  |
| ISO-Chal 97...... | ...                            | ...                      | <0.70                                  |
| ISO-Chal 101..... | ...                            | ...                      | <0.54                                  |
| Ced 110 IRS 2... | ...                            | ...                      | <0.30                                  |

### Table 4

| Name             | $T_{\text{bol}}$ (K) | $V_{\text{LSR}}$ (km s$^{-1}$) | $\Delta V$ (km s$^{-1}$) | $\int T_{\text{bol}}dv$ (K km s$^{-1}$) |
|------------------|----------------------|--------------------------------|--------------------------|----------------------------------------|
| Cha MMS 1......  | 0.26 ± 0.03          | 4.63 ± 0.13                    | 0.36 ± 0.16              | 0.11 ± 0.01                            |
| Ced 110 IRS 4... | 0.13 ± 0.03          | 4.53 ± 0.18                    | 1.72 ± 0.29              | 0.18 ± 0.01                            |

### Table 5

| Name             | $S_{\text{H}_2}^{\text{max}}$ (mJy km s$^{-1}$) | $T_{\text{bol}}$ (K) | $N(H_2)$ (cm$^{-2}$) | $X(\text{HCO}^+)$ |
|------------------|-----------------------------------------------|----------------------|----------------------|-------------------|
| Cha MMS 1......  | 370$^1$                                       | 20$^2$               | 2.2 × 10$^{21}$      | 2.6 × 10$^{-10}$  |
| Ced 110 IRS 4....| 101$^3$                                       | 21$^3$               | 2.8 × 10$^{22}$      | 3.4 × 10$^{-9}$   |

1 Reipurth et al. 1996.
2 Henning et al. 1993.
3 Lehtinen et al. 2001.
to be smaller than the true value. We need to know the inclination angle of this source to correct this mismatch.

4.4. Interaction between Cha-MMS 1 and the Outflow from IRS 4

Figure 1 shows the blueshifted component of the outflow from the IRS 4 has negative spatial correlation with the continuum emission from Cha-MMS 1. The outflow seems to change its direction at the edge of the MMS 1. In Figure 2, the outflow component with the highest velocity is distributed at the midpoint between IRS 4 and MMS 1. In addition, the velocity of the outflow suddenly declines in front of MMS 1 (Fig. 6), i.e., the flow seems to be decelerated by MMS 1. Do these characteristics indicate that MMS 1 interacts with the outflow from IRS 4?

There were no emissions detected from shock tracer molecules in submillimeter wavelength in our observations. However, considering IRS 4's low luminosity ($L_{bol} = 1.0 \, L_\odot$; Lehtinen et al. 2001), weak outflow properties, and high upper velocity levels of >70 K, it is conceivable that the outflow-core interaction could not increase the temperature enough to excite these molecules. We could not rule out that a weak interaction does occur. Kontinen et al. (2000) pointed out that outflows and radiation from the neighboring young stars have prospects for influencing the chemical processes in MMS 1. Here we considered the impact of the interaction from following two viewpoints.

First we investigate momentum. Here we compare the momentum of the outflow and the mass of MMS 1. When an outflow with density $\rho$ and velocity $v$ is colliding with a surface of radius $r$ for a time duration $t$, we obtain the mass $M_{\text{col}}$ colliding in a unit of time and the momentum $P_{\text{outflow}}$ as

$$P_{\text{outflow}} = M_{\text{col}} v t = \pi r^2 v^2 \rho t.$$  (8)

Now we estimate the density of the outflow. For simplicity, we assume the outflow has a cone shape with a base diameter of $40'' (=3.1 \times 10^{-2} \, \text{pc})$ and a height of $60'' (=4.7 \times 10^{-2} \, \text{pc})$ judging from Figure 1. Calculating the density $\rho$ of the outflow from this assumption with the derived mass, we obtain $\rho = 6.5 \times 10^{-20} \, \text{g cm}^{-3}$. Assigning this density, radius $r = 1.6 \times 10^{-2} \, \text{pc}$, and time which equals the dynamical timescale of the flow ($1.0 \times 10^4 \, \text{yr}$) to equation (8), we derived a momentum of 0.88 $M_\odot \, \text{km s}^{-1}$. Meanwhile, the momentum of gas in MMS 1 is calculated to be $P_{\text{MMS1}} = 0.15 M_\odot \, \text{km s}^{-1}$ from the mass of 0.45 $M_\odot$ and the velocity of 0.34 km s$^{-1}$ derived from the $^{13}$CO line profile, which is a combination of turbulence and thermal width, removing the contribution of the spectral resolution. As a result, $P_{\text{outflow}}$ is much larger than $P_{\text{MMS1}}$, which means the motion of the gas in MMS 1 is easily affected when the outflow collides with the core.

Although the MMS 1 contours in Reipurth et al. (1996) have an asymmetry, it is difficult to confirm the collisional impact on the geometry of MMS 1 with their map. But in our HCO$^+$ position-velocity diagram (Fig. 6), we could find the sign of the kinematic motion of the outer gas of MMS 1 caused by the collision. The dip in the northern side of MMS 1 is slightly ($\sim$0.3 km s$^{-1}$) blueshifted, which results in the velocity gradient on the map. This gradient is consistent with the IRS 4 outflow direction. Precise calculations of the momentum for this gradient is difficult with our data set, but in a rough upper limit estimation, the momentum for making this dip velocity gradient, $P_{\text{grad}}$, should be less than the product of the velocity difference and the whole mass of MMS 1, $P_{\text{grad}} < 0.14 M_\odot \, \text{km s}^{-1}$. The momentum provided by the outflow is larger than $P_{\text{grad}}$; thus, this outer gas motion could be excited by the interactions with the outflow.

The other point of discussion is the time needed before induced star formation is triggered in MMS 1. One example of outflow-triggered star formation is L1551 NE in Taurus (Yokogawa et al. 2003). In the case of MMS 1, before star formation is triggered, it is necessary that a rise in pressure outside of MMS 1 by colliding with the outflow reaches the center of the core. The velocity of this propagation equals the sound speed, or the shock speed if a shock has been excited. The sound speed under 10 K is 0.19 km s$^{-1}$. With this velocity, the signal of the collision arrives at the center in 7.2 x $10^4$ yr. This is about an order of magnitude larger than the dynamical timescale of the outflow. Under this condition, triggered star formation would not have occurred yet. Next, we also consider the case in which a shock exists. In order to derive the shock speed, we need to know the density structure around MMS 1, because the shock speed depends on the difference between the inner and outer density of MMS 1. According to Reipurth et al. (1996), the difference between the 1.3 mm continuum intensity at the center and outside of the MMS 1 is about a factor of 2. Under optically thin conditions, the difference of the intensity is identical to that of density, and the shock speed equals half of the outflow speed, 5.3 km s$^{-1}$. With this speed, the shock would arrive at the center in 2.8 x $10^3$ yr from the point of the collision. Considering the time to reach the boundary of MMS 1 from its departure from IRS 4, the time for the outflow to arrive at the center of MMS 1 is 8.5 x $10^3$ yr, about the same as the dynamical timescale of the outflow. If the estimate of density structure is correct, compression has just reached to the center of MMS 1 and collapse would just be triggered. Considering that we could not detect any infall and outflow signature around the source, it is possible that MMS 1 is in a very young stage of its evolution.

### Table 6

| Shift   | $R_{\text{outflow}}$ (pc) | $M$ (M$_\odot$) | $t_{\text{kin}}$ (yr) | $\dot{M}$ (M$_\odot$ yr$^{-1}$) | $P$ (M$_\odot$ km s$^{-1}$) | $E_{\text{kin}}$ (M$_\odot$ km s$^{-1}$)$^2$ | $F$ (M$_\odot$ km s$^{-1}$ yr$^{-1}$) |
|---------|--------------------------|-----------------|------------------------|-----------------------------|------------------------|-----------------------------------|------------------------|
| IRS 4   |                          |                 |                        |                             |                        |                                    |                        |
| Blue    | 6.5 x $10^{-2}$ | 1.1 x $10^{-2}$ | 1.9 x $10^4$ | 1.1 x $10^{-6}$ | 7.1 x $10^{-2}$ | 2.4 x $10^{-1}$ | 7.1 x $10^{-6}$ |
| Red     | 2.5 x $10^{-2}$ | 9.8 x $10^{-4}$ | 2.9 x $10^3$ | 3.4 x $10^{-7}$ | 7.7 x $10^{-3}$ | 3.1 x $10^{-2}$ | 2.7 x $10^{-6}$ |
| IRS 6   |                          |                 |                        |                             |                        |                                    |                        |
| Blue    | 1.6 x $10^{-2}$ | 3.3 x $10^{-4}$ | 7.8 x $10^3$ | 4.3 x $10^{-8}$ | 6.5 x $10^{-4}$ | 6.7 x $10^{-4}$ | 8.4 x $10^{-8}$ |
| Red     | 3.1 x $10^{-2}$ | 5.7 x $10^{-4}$ | 1.3 x $10^4$ | 4.3 x $10^{-8}$ | 1.3 x $10^{-5}$ | 1.5 x $10^{-3}$ | 9.9 x $10^{-8}$ |
5. SUMMARY

We observed a YSO condensation in the Cederblad 110 region of the Chamaeleon I dark cloud by CO($J = 3 \rightarrow 2$), HCO$^+$(J = 4 \rightarrow 3), H$_2$CO*(J = 4 \rightarrow 3), CH$_3$OH*(J = 7K \rightarrow 6K), SO*(J = 8\rightarrow 7K), and SiO*(J = 8 \rightarrow 7) submillimeter lines with the ASTE 10 m telescope. Results are as follows.

1. We found a dense HCO$^+$ clump. This clump is an aggregate made up of three components associated with IRS 4, IRS 11, and Cha-MMS 1. Although these subcomponents do not appear in the integrated intensity map, we can distinguish them in the channel map and the position-velocity diagrams.

2. We detected CO($J = 3 \rightarrow 2$) outflow components around IRS 4 and IRS 6, but not around Cha-MMS 1, IRS 11, or NIR 89. Our observations with high angular resolution show the outflows previously known in this region are launched by IRS 4, not by MMS 1. This result suggests MMS 1 is not a protostar but still in the prestellar phase.

3. Each HCO$^+$(J = 4 \rightarrow 3) line profile toward IRS 4, IRS 11, and MMS 1 all have “red” asymmetry instead of blue asymmetry, which is a marker of infalling gas. However, our result does not necessarily mean there is no inflow in these young sources, because the outflows from IRS 4 and IRS 6 are direct evidence of gas infall.

4. The blueshifted outflow from IRS 4 seems to collide against MMS 1. The outflow veers and the velocity declines just in front of MMS 1. Although emission lines from shock tracer molecules such as CH$_3$OH, SO, and SiO are not detected, it is plausible because the outflow from IRS 4 is rather weak for excitation of these molecules.

5. Momentum calculations show the outflow from IRS 4 is strong enough to affect gas motion in MMS 1, although the outflow is so young that the star formation process has not been triggered yet, or has just been triggered. This is consistent with the very young status of MMS 1 and the lack of any outflows, jets, and masers.

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