1. INTRODUCTION

It is widely accepted that low-mass stars are formed through mass accretion in protostellar envelopes (André et al. 2000; Myers et al. 2000). The dense and warm innermost part of low-mass protostellar envelopes (radius <200 AU) is a likely site of formation of protoplanetary disks (Schaap et al. 1995; Beckwith & Sargent 1996). However, we have very little knowledge about this region, because previous millimeter-wave observations could not separate the warm and dense regions from the overlying low-density (10^2–10^3 cm⁻³) and cold (10 K) gas along the line of sight. On the other hand, millimeter molecular lines such as CS J = 7–6 trace higher densities (10^4–10^5 cm⁻³) and temperatures (≥60 K; Moriarty-Schieven et al. 1995; Schaap et al. 1995), and millimeter dust continuum emission is an excellent tracer of disks around protostars (Osorio et al. 2003).

In this Letter, we describe results of CS J = 7–6 and 343 GHz continuum observations of L1551 IRS 5 with the Submillimeter Array (SMA). L1551 IRS 5 is the brightest protostar (Lbol ~ 30 L☉; Keene & Masson 1990) in Taurus (D ~ 140 pc; Elias 1978). After the first discovery of the bipolar molecular outflow by Snell et al. (1980), Kaifu et al. (1984) discovered a 0.1 pc scale rotating gas structure around L1551 IRS 5 with the Nobeyama 45 m telescope. The elongated rotating protostellar envelope around L1551 IRS 5 was first imaged by Sargent et al. (1988) in C18O J = 1–0 with the Owens Valley Radio Observatory millimeter-array. Ohashi et al. (1996), Saito et al. (1996), and Momose et al. (1998) have found evidence of infalling motion in the protostellar envelope with the Nobeyama Millimeter Array (NMA). Millimeter interferometric observations of dust continuum emission from L1551 IRS 5 revealed that L1551 IRS 5 is a close (~0.3) binary (Looney et al. 1997; Rodríguez et al. 1998). Lay et al. (1994) made the first submillimeter interferometric observations of dust continuum emission from L1551 IRS 5 with the JCMT-CSO interferometer (consisting of the James Clerk Maxwell Telescope and Caltech Submillimeter Observatory). Single-dish observations of L1551 IRS 5 in submillimeter molecular lines have revealed warm (≥20 K) and dense (≥10^5 cm⁻³) gas in the inner part of the envelope (Fuller et al. 1995; Moriarty-Schieven et al. 1995; Hogerheijde et al. 1997, 1998). Our SMA observations provide us with new information on the innermost part of the protostellar envelope.

2. OBSERVATIONS

With the SMA, CS J = 7–6 (342.88295 GHz) and 343 GHz continuum observations of L1551 IRS 5 were made on 2002 December 18 and 2003 March 13. Details of the SMA are described by Ho et al. (2004). Table 1 summarizes the observational parameters. We confirmed that the visibility amplitudes of the continuum emission from L1551 IRS 5 at the two observing periods were consistent within the noise level. The overall flux uncertainty was estimated to be about 20%. Since the minimum baseline length projected on the sky was 14.8 kλ, our observations were insensitive to structures more extended than 11'' (~1500 AU) at the 10% level (Wilner & Welch 1994).

The raw visibility data were calibrated and flagged with MIR, and the calibrated visibility data were Fourier-transformed and CLEANed with MIRIAD. We adopted robust (r = 0.5) weighting for the imaging, which seemed to provide the best compromise between the sensitivity and the spatial resolution. The rms noise levels of the images were about twice what is expected, for reasons that are under investigation.

SUBMILLIMETER ARRAY OBSERVATIONS OF L1551 IRS 5 IN CS J = 7–6

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ABSTRACT

We have imaged the circumstellar envelope around the binary protostar L1551 IRS 5 in CS J = 7–6 and 343 GHz continuum emission at ∼3'' resolution using the Submillimeter Array. The continuum emission shows an elongated structure (∼220 × 100 AU) around the binary perpendicular to the axis of the associated radio jet. The CS emission extends over ∼400 AU, appears approximately circularly symmetric, and shows a velocity gradient from southeast (blueshifted) to northwest (redshifted). The direction of the velocity gradient is different from that observed in C18O J = 1–0. This may be because rotation is more dominant in the CS envelope than the C18O envelope, in which both infall and rotation exist. The CS emission can be divided into two velocity components: (1) a “high”-velocity disklike structure surrounding the protostar ±1.0–1.5 km s⁻¹ from the systemic velocity, and (2) a “low”-velocity structure located southwest of the protostar less than 1.0 km s⁻¹ from the systemic velocity. The high-velocity component traces warm and dense gas with kinematics consistent with rotation around the protostar. The low-velocity component may arise from dense gas entrained in the outflow. Alternatively, this component may trace infalling and rotating gas in an envelope with a vertical structure.

Subject headings: ISM: individual (L1551 IRS 5) — ISM: molecules — planetary systems: protoplanetary disks — stars: formation

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In Figure 1, we show the total integrated intensity map of the CS J = 7–6 emission along with the C18O J = 1–0 map taken with the NMA by Momose et al. (1998). While the C18O map reveals a structure of the protostellar envelope elongated (∼2400 × 1000 AU in size) perpendicularly to the axis of the associated molecular outflow (Uchida et al. 1987; Moriarty-Schieven & Snell 1988), the CS emission shows a structure without clear elongation. From the elliptical Gaussian fitting, the size of this CS condensation deconvolved by the synthesized beam was derived as ∼3′′ × 2′′ (P.A. = 40°), which corresponds to a diameter of ∼400 AU at the distance of L1551 IRS 5. Comparison of the SMA flux to the total flux of the CSO CS J = 7–6 spectrum toward L1551 IRS 5 suggests that ∼1% of the single-dish flux is recovered by the SMA at ∼3″ resolution.

In Figure 2, we show the intensity-weighted mean velocity map of L1551 IRS 5 in the CS emission. There is a clear velocity gradient from southeast to northwest, which is perpendicular to the axis of the associated molecular outflow (northeast-southwest; Uchida et al. 1987; Moriarty-Schieven & Snell 1988). This direction of the velocity gradient is different from that observed in the C18O emission (Momose et al. 1998); e.g., the C18O envelope shows a velocity gradient from south to north near the central star. The reason for this difference may be because the CS envelope is more dominated by rotation than the C18O envelope, which is dominated by infall as well as rotation.

In order to understand the velocity structure better, we made velocity channel maps of the CS emission at different velocity ranges; that is, a “high-velocity” (5.3–5.85 and 7.82–8.35 km s⁻¹) component and a “low-velocity” (6.39–6.74 and 6.92–7.28 km s⁻¹) component. In Figure 3, we show the high- and low-velocity components separately, superposed on the 343 GHz dust continuum emission and the VLA 3.5 cm radio jet image (Rodríguez et al. 2003b). The total 343 GHz continuum flux is 2.2 Jy with a deconvolved size of 1′.6 × 0′′7 (220 × 100 AU) at P.A. = −97°, derived from the elliptical Gaussian fitting. The flux and size are consistent with the estimates from the JCMT-CSO interferometric study (Lay et al. 1994), and the dust emission most likely represents the circumbinary disk and the circumstellar disks associated with the protostars, although the circumstellar disks are not spatially resolved. The high-velocity component in the CS emission spatially coincides with the dust continuum distribution, which is approximately perpendicular to the axis of the radio jet (Rodríguez et al. 2003b). On the other hand, there is a slight but significant spatial discrepancy between the low-velocity component and the dust continuum emission, wherein the low-velocity component is located to the southwest of the dust disk. The peak of the redshifted low-velocity component seems to lie along the axis of the radio jet.

3. RESULTS

TABLE 1

| Parameter                        | Value          |
|----------------------------------|----------------|
| Number of antennas              | 3              |
| Right ascension (J2000)          | 04°31′34″14″   |
| Declination (J2000)              | 18°08′05″1″    |
| Primary beam HPBW               | ∼40°           |
| Synthesized beam HPBW            | 3′′ × 2′′ (P.A. = −60°) |
| Conversion factor                | 1 Jy beam⁻¹ = 1.6 (K) |
| Frequency resolution            | 203.125 kHz, ∼0.178 km s⁻¹ |
| Bandwidth                        | 82 MHz × 4 e 82 MHz × 8 |
| Gain calibrator                  | Quasar 0423    |
| Flux of the gain calibrator      | 7.8 Jy         |
| Passband calibrator              | Saturn         |
| Flux calibrator                  | Uranus         |
| System temperature (DSB)         | 0.2 Jy beam⁻¹ |
| rms noise level (continuum)      | 0.02 Jy beam⁻¹ |
| rms noise level (continuum)      | 1.2 Jy beam⁻¹/203.125 kHz |

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Note.—HPBW = half-power beamwidth; DSB = double sideband.

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FIG. 1.—Total integrated intensity map of the CS J = 7–6 emission of L1551 IRS 5 taken with the SMA (pseudocolor and black contour) with the C18O J = 1–0 total intensity map taken with the NMA by Momose et al. (1998; light blue contour). Contour levels of the SMA observations are from 3.0 Jy beam⁻¹ km s⁻¹ in steps of 2.0 Jy beam⁻¹ km s⁻¹. White crosses indicate the position of the binary (Rodríguez et al. 1998). The SMA-synthesized beam is shown at lower right, and the NMA-synthesized beam at lower left.

FIG. 2.—CS J = 7–6 intensity-weighted mean velocity map in L1551 IRS 5. Contour levels are from 5.8 km s⁻¹ in steps of 0.2 km s⁻¹. Crosses indicate the position of the binary. There is clear velocity gradient from southeast (blue) to northwest (red).
4. DISCUSSION

4.1. Physical Conditions of the CS-emitting Region

Our CS $J = 7$–$6$ observations have revealed a rather compact ($\sim$400 AU) structure in the inner part of the elongated ($\sim$2000 AU) protostellar envelope detected by millimeter-wave observations (Ohashi et al. 1996; Saito et al. 1996; Momose et al. 1998) around L1551 IRS 5. The critical gas density traced by the CS line is expected to be $\gtrsim 10^7$ cm$^{-3}$, and the equivalent temperature of the $J = 7$ energy level is 66 K. This gas density and temperature are much higher than those traced by the millimeter-wave tracers, such as C$^{18}$O $J = 1$–$0$ ($\sim 10^6$ cm$^{-3}$; 5 K; Sargent et al. 1988; Momose et al. 1998) or H$^{13}$CO$^+$ $J = 1$–$0$ ($\sim 10^5$ cm$^{-3}$; 4 K; Saito et al. 1996). Indeed, Moriarty-Schieven et al. (1995) estimated gas density and temperature at the center of the envelope in L1551 IRS 5 to be $\sim 10^7$ cm$^{-3}$ and $\sim 40$ K from their multitransitional CS $J = 3$–$2$, 5–4, and 7–6 observations with JCMT and CSO. Part of the difference in the distribution between the CS $J = 7$–$6$ and C$^{18}$O $J = 1$–$0$ emission shown in Figure 1 is likely to be due to the different physical conditions traced by these two molecular lines. The CS emission line traces better the inner denser and warmer part of the protostellar envelope.

The compact shape of the CS $J = 7$–$6$ emission without elongation could be due to the missing flux (only $\sim$11% recovered). However, our simple simulation indicated that if the distribution of the CS $J = 7$–$6$ emission were the same as that of the C$^{18}$O $J = 1$–$0$ emission, then the present SMA observations would not detect any of the CS emission. This suggests that there should be a compact structure of the CS emission, as well as an extended CS component with $\gtrsim 1''$ = 1500 AU in size. We note that it is still a puzzle why the CS $J = 7$–$6$ emission, which traces denser and warmer gas, can be so extended. It seems to be difficult to make gas temperatures high enough strictly via heating from the central stars (e.g., Lay et al. 1994). There might be some external heating sources such as shocks due to infalling and/or outflowing gas (Nakamura 2000; Avery & Chiao 1996).

4.2. Origin of the High- and Low-Velocity Components

As described in § 3, the CS $J = 7$–$6$ emission in L1551 IRS 5 consists of a high-velocity disklike component and a low-velocity component whose peak is located at the southwest of the protostar. In order to investigate the origin of these velocity components in more detail, in Figure 4 we show the position-velocity ($P$-$V$) diagram of the CS emission along the cut perpendicular to the axis of the radio jet (see Fig. 3). The velocity structure appears to be symmetric with respect to the velocity of 6.8 km s$^{-1}$, and we adopt this velocity as a systemic velocity in this Letter (note that this is significantly different from the systemic velocity of C$^{18}$O $J = 1$–$0$ of 6.2 km s$^{-1}$; Momose et al. 1998). Solid color curves in Figure 4 indicate the Keplerian rotation velocity ($\propto r^{-0.5}$) for a disk with an inclination angle of 65° (Momose et al. 1998) and with a central stellar mass of 0.15 $M_\odot$ (red), 0.5 $M_\odot$ (green), and 1.2 $M_\odot$ (blue). The central stellar mass of 0.15 $M_\odot$ was estimated by Momose et al. (1998) from their detailed kinematic analyses of the C$^{18}$O infalling envelope, and that of 1.2 $M_\odot$ by Rodríguez et al. (2003a) from the proper-motion analyses of the binary. Dashed curves in Figure 4 show rotation with angular momentum conserved; that is, $V_{\text{rot}} = 0.24(r/700$ AU$)^{1.5}$ km s$^{-1}$. Momose et al. (1998) argued that this rotation law can explain the observed $P$-$V$ diagram of the C$^{18}$O infalling envelope. The high-velocity component, with relative velocities of $\pm 1.0$–$1.5$ km s$^{-1}$ in Figure 4, seems to be consistent with a Keplerian rotation with a central stellar mass of 0.15 $M_\odot$ or a rotation with the constant angular momentum, and is likely to be the rotating circumbinary disk at the innermost part of the envelope. Unfortunately, it is difficult for us to distinguish these two rotation curves to explain the kinematics of the high-velocity component given the current sensitivity. Keplerian rotation curves with higher ($>1.0$ $M_\odot$) stellar masses show velocities that are too high compared to the CS $P$-$V$ diagram.

In contrast, the low-velocity component ($\pm 0.5$ km s$^{-1}$ from the systemic velocity) seems to not follow these rotation curves. The spatial offset of the low-velocity component from the dust disk, and the possible coincidence with the radio jet (Fig. 3), may suggest that the origin of the low-velocity component is outflow-related. Interestingly, at the southwestern tip of the radio jet where the peaks of the low-velocity component are located, Bally et al. (2003) have detected X-ray emission with Chandra
Fig. 4.—$P-V$ diagram of the CS $J = 7-6$ emission along the major axis (P.A. = 162°; see Fig. 3) in L1551 IRS 5. Contour levels are from 2.3 Jy beam$^{-1}$ in steps of 1.15 Jy beam$^{-1}$. Solid color curves indicate the Keplerian rotation velocity (or $^{-5}$) with a central stellar mass of $0.15 M_\odot$ (red), $0.5 M_\odot$ (green), and $1.2 M_\odot$ (blue), and an inclination angle of 65°, while dashed curves indicate rotation with angular momentum conservation as given by $V_{\text{circ}}$ in the text.

that they attribute to shocks caused by the jet. One interpretation, therefore, is that the low-velocity component is the shocked warm and dense molecular material pushed by the radio jet. However, one difficulty of this interpretation may be its "low velocity." The projected separation between the peaks of the low-velocity component and the continuum peak is $\sim100$ AU, and the line-of-sight velocities of the low-velocity component is only about a few $\times 0.1$ km s$^{-1}$. In order for the low-velocity component to escape from the gravitational potential of the central star with a mass of $0.15 M_\odot$ (Momose et al. 1998), the angle between the flow and the plane of the sky must be less than 10°, while Uchida et al. (1987) estimated the inclination angle of 15° from their large-scale CO outflow map.

It is important to compare our $P-V$ diagram with those calculated using a model envelope with a vertical structure, because models of flared envelopes having infall as well as rotation yield peaks at lower velocity near the central star in their $P-V$ diagrams cut along the major axis (Momose et al. 1998; Hogerheijde 2001). The reason why these peaks at lower velocity appear near the central star is because infalling motions in the near and far side of the envelope are observed together with rotation in the same line of sight. These peaks cannot be explained with rotation curves calculated using spatially thin disk models, which is very similar to our case shown in Figure 4. It is therefore possible that a model envelope having vertical structures with infall and rotation motions may explain the lower velocity component.

The effect of the missing flux prevents us from arriving at a clear interpretation. The lower velocity component could be part of spatially extended component, which can often be seen at lower velocities. Further observations with shorter spacings using the SMA should provide us a clearer view and interpretation of these velocity structures of warm and dense gas in the innermost part of the protostellar envelope.

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