DISPERSING ENVELOPE AROUND THE KEPLERIAN CIRCUMBINARY DISK IN L1551 NE AND ITS IMPLICATIONS FOR BINARY GROWTH

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Received 2015 June 22; accepted 2015 October 20; published 2015 December 1

ABSTRACT

We performed mapping observations of the Class I protostellar binary system L1551 NE in the $^{13}$CO ($J = 3–2$), $^{13}$CO ($J = 3–2$), CS ($J = 7–6$), and SO ($J_N = 7_N–6_N$) lines with the Atacama Submillimeter Telescope Experiment (ASTE). The ASTE $^{13}$CO data were combined with our previous SMA $^{13}$CO data, which show a $r \approx 300$ AU scale Keplerian disk around the protostellar binary system. The $^{13}$CO maps show a $\sim20,000$ AU scale protostellar envelope surrounding the central Keplerian circumbinary disk. The envelope exhibits a northeast (blue) to southwest (red) velocity gradient along the minor axis, which can be interpreted as a dispersing gas motion with an outward velocity of $0.3 \text{ km s}^{-1}$, while no rotational motion in the envelope is seen. In addition to the envelope, two $\lesssim 4000$ AU scale, high-velocity ($\gtrsim 1.3 \text{ km s}^{-1}$) redshifted $^{13}$CO and CS emission components are found $\sim 40''$ southwest and $\sim 20''$ west of the protostellar binary. These redshifted components are most likely outflow components driven from the neighboring protostellar source L1551 IRS 5, and are colliding with the envelope in L1551 NE. The net momentum, kinetic, and internal energies of the L1551 IRS 5 outflow components are comparable to those of the L1551 NE envelope, and the interactions between the outflows and the envelope are likely to cause the dissipation of the envelope and thus suppression of further growth of the mass and mass ratio of the central protostellar binary in L1551 NE.

Key words: ISM: individual objects (L1551 NE) – ISM: molecules – stars: formation

1. INTRODUCTION

The physical mechanisms to set the mass ratios of binary stars are of fundamental astrophysical importance, since more than half of main-sequence, pre-main-sequence, and even protostars with masses comparable to the solar mass are members of binary systems (Raghavan et al. 2010; Chen et al. 2013; Reipurth et al. 2014). Binary stars with primary masses comparable to the solar mass exhibit a wide, essentially flat, distribution of mass ratios ($q$) from $q \sim 0.1–1$ (Raghavan et al. 2010; Goodwin 2013). The physical processes to reproduce such a flat distribution of the binary mass ratios are, however, still controversial.

Protostellar binary systems, precursors of main-sequence binary systems, are often surrounded by disks of molecular gas and dusts, “circuminary disks” (hereafter CBDs; Takakuwa et al. 2012, 2014; Tobin et al. 2013; Chou et al. 2014; Dutrey et al. 2014; Tang et al. 2014). The radii of these CBDs range from $\lesssim 100$ to $\sim 500$ AU, and these CBDs often show inner emission depressions and ring-like structures. Mass accretion from these CBDs onto the protostellar binary is essential to properly trace the mass accretion, since accreting gas flows into the binary through these Lagrangian points. On the other hand, latest SPH simulations have demonstrated that mass accretion in CBDs is a function of gas temperatures, and in the case of high temperatures the primary accretes more than the secondary, and vice versa (Young et al. 2015). Young et al. (2015) argued that the difference between the above results can simply be explained by the difference of the adopted gas temperatures in the models. It has been still controversial to construct a consistent, unified model of mass accretion from CBDs onto protostellar binaries.

CBDs in protostellar binary systems are considered to be embedded in larger scale protostellar envelopes, which can replenish the central CBDs with fresh materials (Momose et al. 1998; Chou et al. 2014; Tang et al. 2014). Since the observed masses of CBDs around protostellar binaries ($\lesssim 0.1 M_\odot$) are much smaller than the masses of the central protostellar binaries (Takakuwa et al. 2012; Tobin et al. 2013; Chou et al. 2014), further supply of materials from the protostellar envelopes to the CBDs is essential to significantly change the mass and mass ratios of the protostellar binaries. If a protostellar envelope keeps supplying materials to the central CBD, further growth of the mass and mass ratio of the protostellar binary will be expected. On the other hand, if most of the envelope materials are being dissipated, the present mass and mass ratio of the protostellar binary will be close to the final values. Such dissipations of protostellar envelopes through the interactions with the associated outflows or stellar winds have been investigated observationally (Kitamura...
et al. 1996; Momose et al. 1996; Fuente et al. 2002; Takakuwa et al. 2003; Arce & Sargent 2006; Takahashi et al. 2006). Thus, in addition to the physics of accretion from CBSD onto the protostellar binaries, mass replenishment from the surrounding protostellar envelopes and the connection between protostellar envelopes and CBSDs must be taken into account.

In the present paper, we focus on a protostellar envelope harboring the protostellar binary system L1551 NE. L1551 NE is a young Class I protostellar binary \( (T_{\text{bol}} = 91 \text{ K}, L_{\text{bol}} = 4.2 L_{\odot}; \text{Froebrich 2005}) \) located to \( \sim 2/5 \) northeast of the brightest protostellar binary L1551 IRS 5 in the L1551 region (Saito et al. 2001; Reipurth et al. 2002; Takakuwa et al. 2004; Hayashi & Pyo 2009; Chou et al. 2014). The protostellar binary consists of the northwestern source called “Source A,” and the southeastern source “Source B,” with the projected separation of \( \sim 70 \text{ AU} \) at a position angle of \( 300^\circ \) (Reipurth et al. 2002; Takakuwa et al. 2014). Our previous SMA observations of L1551 NE have identified a \( r \sim 300 \text{ AU} \) scale CBD in Keplerian rotation with a central stellar mass of \( 0.8 M_{\odot} \) (Takakuwa et al. 2012), plus a possible outer infalling component (Takakuwa et al. 2013). Our subsequent ALMA Cycle 0 observation of L1551 NE (Takakuwa et al. 2014), at a spatial resolution that is \( \sim 1.6 \) times higher (in beam area) and a sensitivity that is \( \sim 6 \) times better (in brightness temperature) than those attained in our previous SMA observations, unveiled substructures of the CBD in the \( 0.9 \text{ mm} \) dust continuum emission. The revealed substructures are consistent with our three-dimensional (3D) adaptive mesh refinement (AMR) hydrodynamic simulation (Matsumoto 2007) for the presence of two spiral arms driven by gravitational torques from the central binary system. The ALMA data of L1551 NE in the \(^{13}\text{CO} \text{(3--2)} \) line also exhibits the deviations from the Keplerian motion in the CBD, consistent with our AMR simulation that gravitational torques impart angular momenta along the spiral arms (driving material outwards) and extract angular momenta between the spiral arms (driving infall). Our theoretical model, which reproduces the observed features of the CBD around L1551 NE, predicts that the secondary accretes more than the primary. Since our series of the SMA and ALMA observations of L1551 NE have revealed the CBD + protostellar binary system, the next question is the connection from the protostellar envelope to the CBD, and the mass replenishment from the envelope to the CBD.

We conducted single-dish mapping observations of the protostellar envelope surrounding the protostellar binary system of L1551 NE in the \(^{13}\text{CO} \text{(J = 3--2)}, \, ^{13}\text{CO} \text{(J = 3--2)}, \, \text{CS} \text{(J = 7--6)}, \) and the SO (\( J_N = 7_6--6_7; \, 340.71416 \text{ GHz} \), and the CS (\( J = 7--6; \, 342.882857 \text{ GHz} \)) lines with the ASTE 10m telescope on 2013 September 23–26 and October 4. Remote observations were performed from the ASTE operation room of NAOJ at Mitaka, Japan, using the network observation system N-COSMOS3 developed by NAOJ (Kamazaki et al. 2005). A cartridge-type, double-sideband 350 GHz receiver with an IF frequency range of 4.5–7 GHz (CATS345) mounted on ASTE (Kohno 2005) was used, and all the four lines were observed simultaneously, except on September 23 when only the SO and CS lines were observed due to an error of the instrumental setting. We used only the data with the DSB system noise temperature ranging \( \sim 200--800 \text{ K} \), and the data with the higher noise temperatures were excluded. The telescope pointing was checked every \( \sim 1.5--2 \text{ hr} \) by five-point CO (\( J = 3--2 \)) observations of a late-type star, NML-Tau, and was found to be better than \( \sim 2'' \). As a standard source, we also observed Orion KL (Schilke et al. 1997) and L1551 IRS 5 (Takakuwa & Kamazaki 2011), and confirmed that the relative intensity was consistent within \( \sim 50\% \) with a main beam efficiency of 0.6. No further correction for the sideband ratio was performed. Hereafter we show the observed line intensities in units of \( T_{\text{MB}} \).

The observations consisted of two parts; one-point, deep observations toward the center of L1551 NE (\( \alpha_{2000} = 04^h31^m44^s47, \, \delta_{2000} = 18^\circ08'32''2, \) which is the field center of our previous SMA observations and matches approximately the positions of the protostellar binary (Takakuwa et al. 2012, 2013), and mapping observations around L1551 NE. Both observations were conducted in the position-switching mode. The SO and CS line data toward the center of L1551 NE taken on September 23, when the other line data were not taken due to the error of the instrumental setting, are included in the deep integrations. The resultant total on-source integration time of the SO and CS data toward the center of L1551 NE is 1620 s, while that of the \(^{13}\text{CO} \) and \(^{18}\text{O} \) data is 1220 s. The rms noise levels of the \(^{13}\text{CO}, \, ^{18}\text{O}, \) SO, and the CS spectra toward the center of L1551 NE are 0.055 K, 0.062 K, 0.02 K, and 0.029 K, respectively. The mapping observations were conducted with a grid spacing of \( 10'' \) (Nyquist sampling), and a typical on-source integration time per point of \( \sim 80 \text{ s} \). The map center is set to be the position of the deep integrations. The spatial and spectral resolutions and the noise level of the mapping observations in the \(^{18}\text{O} \) line are summarized in Table 1.

We combined the ASTE image cube in the \(^{18}\text{O} \) line with the interferometric \(^{18}\text{O} \) data of L1551 NE taken with the

| Parameter | ASTE | ASTE + SMA |
|-----------|------|------------|
| Beam      | 23'' | 2''85 x 2''45 (P.A. = -85'3) |
| Velocity Resolution | 0.114 km s\(^{-1}\) | 0.185 km s\(^{-1}\) |
| Noise Level | 0.18 K | 0.60 K |

Table 1: Resolutions and Noise Levels of the \(^{18}\text{O} \) (3--2) Image Cubes
SMA in its subcompact and compact configurations (Takakuwa et al. 2013), adopting the method described by Takakuwa et al. (2007b). Details of the SMA observations are described by Takakuwa et al. (2013). The conversion factor from $T_{MB}$ (K) to $S$ (Jy beam$^{-1}$) was derived to be 48.5 as 

$$S = \frac{2k_B \Omega_{beam}}{\lambda^2} T_{MB},$$

where $k_B$ is the Boltzmann constant, $\lambda$ is the wavelength, and $\Omega_{beam}$ is the solid angle of the ASTE beam ($= 23''$). The spatial and spectral resolutions and the noise level of the combined SMA+ASTE image cube in the C$^{18}$O line are summarized in Table 1.

3. RESULTS

3.1. ASTE Spectra toward L1551 NE

Figure 1 shows the observed ASTE spectra of the C$^{18}$O (J = 3–2), $^{13}$CO (J = 3–2), CS (J = 7–6), and the SO (J$_N$ = 7$_B$–6$_B$) lines toward the protobinary of L1551 NE. The C$^{18}$O spectrum appears to consist of narrow and wide components. Two-component Gaussian fitting to the C$^{18}$O spectrum shows that the peak brightness temperature, line width, and the centroid velocity of the narrow component are 2.4 K, 0.72 km s$^{-1}$, and 6.68 km s$^{-1}$, and those of the wide component are 1.1 K, 2.24 km s$^{-1}$, and 6.99 km s$^{-1}$, respectively (light lines in Figure 1). Previous CSO observations also found that the C$^{18}$O (3–2) spectrum toward L1551 NE can be decomposed of two Gaussian components with similar line widths and centroid velocities (Fuller & Ladd 2002). In particular, the centroid velocity of the broad component is similar to the centroid velocity of the CBD derived from our previous SMA observations ($= 6.9$ km s$^{-1}$; Takakuwa et al. 2012, 2013). As shown in the next subsection, the broad C$^{18}$O component is present only toward the protobinary position. These results indicate that the broader component in the ASTE C$^{18}$O spectrum likely originates from the central CBD. On the other hand, the narrower C$^{18}$O component traces a distinct component at a slightly blueshifted ($\sim 0.2$ km s$^{-1}$) centroid velocity. As shown below, this narrow component traces the extended envelope component around L1551 NE. Hereafter in this paper, $V_{LSR} = 6.7$ km s$^{-1}$ is adopted as the systemic velocity of the extended envelope component, while $V_{LSR} = 6.9$ km s$^{-1}$ is adopted as the systemic velocity of the CBD in L1551 NE.

The $^{13}$CO (J = 3–2) spectrum shows an absorption dip at around the centroid velocity of the narrow component of the C$^{18}$O spectrum, and a broad redshifted wing up to $V_{LSR} \sim 13$ km s$^{-1}$. While part of the redshifted wing in the $^{13}$CO spectrum likely originates from the CBD as in the case of the C$^{18}$O spectrum, mapping observations of the $^{13}$CO line demonstrate that the redshifted $^{13}$CO emission is most likely arising from the outflow component driven from L1551 IRS 5, as will be discussed below. With a deeper integration, a much better CS (J = 7–6) spectrum of L1551 NE than our previous one (Takakuwa & Kamazaki 2011) is obtained. The CS

![Figure 1. ASTE spectra toward the central position of L1551 NE. Light lines at the bottom show the results of the two-component Gaussian fitting to the observed C$^{18}$O (3–2) spectrum. The vertical dashed lines denote the centroid velocities of the envelope ($V_{LSR} = 6.7$ km s$^{-1}$) and the central circumbinary disk ($V_{LSR} = 6.9$ km s$^{-1}$).](image-url)
spectrum shows a non-Gaussian, flat-top spectral shape. Whereas the SO \((J_N = 7_8-6_7)\) line is weak compared to the other lines, the peak intensity (\(\sim 0.14 \text{ K}\)) is detected above 5.5\(\sigma\).

3.2. Spatial and Velocity Distributions Observed with ASTE

Figure 2 shows total integrated intensity maps of the four molecular lines observed with ASTE. The \(^{13}\text{CO} (3-2)\) emission exhibits condensed and diffuse components, the former of which is centered on the protobinary position. Two-components, 2D Gaussian fitting to the \(^{13}\text{CO}\) total integrated map shows that the \(^{13}\text{CO}\) emission can be decomposed of a central component with a size of \(\sim 5500 \text{ AU} \times 2600 \text{ AU} (\text{P.A.} = -46^\circ)\) and a diffuse component with a size of \(\sim 21,000 \text{ AU}\). Emission peaks toward the protostellar position are also seen in the CS (7–6) and SO (7_8-6_7) lines. On the other hand, the \(^{13}\text{CO} (3-2)\) peak emission does not coincide with the protostellar position but is offset at \(\sim 20''\) west from the protostar. The \(^{13}\text{CO}\) emission shows an elongated feature toward the southwest direction, which is also evident in the \(^{13}\text{CO}\) and CS emission.

Figure 3 shows the ASTE velocity channel maps of the \(^{13}\text{CO} (3-2)\) line at a velocity interval of 0.455 km s\(^{-1}\). In the blueshifted velocity range \((V_{\text{LSR}} = 4.62-5.99 \text{ km s}^{-1})\), an emission component to the northwest of the protostar and that centered on the protostellar position are seen. Around the systemic velocity \((6.45-6.90 \text{ km s}^{-1})\) the \(^{13}\text{CO}\) line shows less intensity contrast, suggesting that the \(^{13}\text{CO}\) emission traces the overall cloud component. In the redshifted velocity of 7.36–9.18 km s\(^{-1}\), two
emission components, one located $\sim 20''$ west of the protostar and the other to $\sim 40''$ southwest, are seen. While the southwestern component diminishes at velocities higher than $9.63 \text{ km s}^{-1}$, the western component is seen until $\sim 12.36 \text{ km s}^{-1}$. The location and velocity of this high-velocity redshifted component is consistent with those of a redshifted
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Figure 5. Same as Figure 3 but for the CS (7–6) line. Contour levels start from 2σ in steps of 2σ (1σ = 0.050 K).

outflow component seen in the $^{12}$CO (1–0; 2–1; 3–2) lines (Moriarty-Schieven et al. 2006; Stojimirović et al. 2006) and the CS (2–1; 3–2) lines (Plambeck & Snell 1995; Yokogawa et al. 2003) driven from the neighboring protostellar source, L1551 IRS 5. Thus, the high-velocity redshifted component seen in the $^{13}$CO line most likely traces the redshifted outflow component from L1551 IRS 5.

Figure 4 shows the ASTE velocity channel maps of the C$^{18}$O line at the same velocity bin as that of the $^{13}$CO velocity channel maps. The C$^{18}$O emission component associated with the protostar is seen from $V_{\text{LSR}} = 5.53$ km s$^{-1}$. The C$^{18}$O emission component exhibits an elongated feature at 6.44–6.90 km s$^{-1}$ along the northeast to the southeast direction, which is approximately consistent with the major axis of the central disk. While the C$^{18}$O emission peak at 6.44 km s$^{-1}$ is located to the northeast of the protostar, the emission location is systematically shifted from northeast to southwest from the blueshifted to redshifted velocities (6.44–7.81 km s$^{-1}$). These results indicate that there is a velocity gradient in the C$^{18}$O emission along the direction of the minor axis of the central disk. These C$^{18}$O emission components most likely trace the protostellar envelope surrounding L1551 NE (hereafter “ENV”). In the redshifted velocities from 7.35 km s$^{-1}$, another emission component to the southwest of the protostar becomes evident. This component appears to trace the same southwestern gas component seen in the $^{13}$CO emission. In even higher redshifted velocities (8.72–10.54 km s$^{-1}$), the C$^{18}$O counterpart of the western redshifted component found in the $^{13}$CO emission is also seen, although the highest velocity end of the C$^{18}$O counterpart is lower than that of the $^{13}$CO emission.

Figure 5 shows the same velocity channel maps as those of Figures 3 and 4 but for the CS (7–6) line. While the CS emission traces a gas component associated with the protostar in the velocity range of 5.54–7.81 km s$^{-1}$, the most prominent CS emission component is the redshifted (8.27–9.18 km s$^{-1}$) component to the southwest of the protostar. This southwestern redshifted component is also seen in the $^{13}$CO and C$^{18}$O emission. Previous BIMA and NMA observations of the CS (2–1; 3–2) lines have also found the same CS component, where the CS abundance is enhanced by a factor of a few (Plambeck & Snell 1995; Yokogawa et al. 2003). This CS component is considered to be shock-excited molecular gas of the outflow driven from L1551 IRS 5 (Plambeck & Snell 1995). The detection of the submillimeter CS (7–6) emission with the present ASTE observations, which traces warm ($\gtrsim 60$ K) molecular gas (Takakuwa et al. 2007a; Takakuwa & Kamazaki 2011), further supports this interpretation. Hereafter we call this redshifted component to the southwest of the protostar “RED1,” and the highest velocity redshifted component seen in the $^{13}$CO and C$^{18}$O lines to the west of the protostar “RED2.”

In Figure 6, we compare spatial distributions of ENV as seen in the C$^{18}$O emission, RED1 in the $^{13}$CO emission, and RED2 in the $^{13}$CO emission. Line profiles in the peak positions of RED1 and RED2, as well as those 20″ east of the protostar, are also shown (note that the line profiles of ENV are shown in Figure 1.). The two outflow components of RED1 and RED2 are located to the western side of ENV. Toward RED1, the $^{13}$CO line profile shows an intense redshifted peak plus a red wing up to $V_{\text{LSR}} \sim 12$ km s$^{-1}$. The C$^{18}$O line profile exhibits redshifted emission “plateau” up to $V_{\text{LSR}} \sim 10$ km s$^{-1}$, and the CS line profile shows the emission only in the redshifted velocity range. A similar $^{13}$CO redshifted wing and C$^{18}$O emission plateau are also seen toward RED2, where a weak redshifted CS emission is also present. On the other hand, toward the 20″ east of the protostar, such a C$^{18}$O emission plateau is not seen and the $^{13}$CO redshifted
Figure 6. Maps of the envelope component in the C$^{18}$O (3–2) line (black contours), the high-velocity redshifted component in the $^{13}$CO (3–2) line (purple contours), and the redshifted CS (7–6) component (red contours) along with the line profiles toward the representative positions marked with crosses. Velocity ranges of the C$^{18}$O, $^{13}$CO, and the CS maps are 5.31–8.15 km s$^{-1}$, 9.47–12.53 km s$^{-1}$, and 8.04–9.13 km s$^{-1}$, respectively. Contour levels start from 5$\sigma$ in steps of 5$\sigma$ in the C$^{18}$O map (1$\sigma$ = 0.036 K), 5$\sigma$ in steps of 10$\sigma$ in the $^{13}$CO map (1$\sigma$ = 0.028 K), and 4$\sigma$ in steps of 3$\sigma$ in the CS map (1$\sigma$ = 0.032 K). A large cross and a filled circle at the bottom right corner denote the protostellar position and the ASTE beam in the C$^{18}$O map, respectively. Vertical dashed lines in the spectra show the systemic velocity of the envelope of $V_{\text{LSR}}$ = 6.7 km s$^{-1}$.

wing is much less prominent, and the submillimeter CS emission is not detected. These results imply that the outflow streams of RED1 and RED2 are terminated at the western side of ENV. One possible interpretation for this termination is the collision between the outflows of RED1 and RED2.

In Figure 7, we show the Position–Velocity (P–V) diagrams of the $^{13}$CO, C$^{18}$O, and the CS lines along the cuts passing through the protostellar position and the peak positions of RED1 (P. A. = 45°) and RED2 (P.A. = 90°). In the C$^{18}$O P–Vs the envelope component is seen as labeled. To the west of ENV the $^{13}$CO, C$^{18}$O, and the CS emission components arising from RED1 and RED2 appear as delineated by dashed lines, and the velocities of RED1 and RED2 become closer to the systemic velocity as the positions become closer to ENV. These results suggest that the flow velocities of RED1 and RED2 are decelerated as they become close to ENV, presumably due to the collision with ENV.

Figure 8 shows ASTE P–V diagrams of the C$^{18}$O and $^{13}$CO lines along the major and minor axes of the central CBD passing through the protostellar position. In the C$^{18}$O P–Vs, the line broadening at the protostellar position arising from the CBD is clearly seen, and the velocity gradient originated from the Keplerian rotation (blue curves in Figure 8) can be identified along the major axis. As discussed in the C$^{18}$O line profile toward the protostellar position (Figure 1), the centroid velocity of the CBD component and that of the envelope component are offset by $\sim$0.2 km s$^{-1}$ (two vertical dashed lines in Figure 8), and the C$^{18}$O P–Vs exhibit this offset clearly. Furthermore, along the major axis the envelope component as seen in the C$^{18}$O emission does not show any noticeable velocity gradient, and the Keplerian rotation of the central disk is not continuous to the outer envelope. On the other hand, along the minor axis the C$^{18}$O envelope shows a clear velocity gradient along the northeast (blue) to southwest (red) direction (tilted black dashed line in Figure 8). Since the associated NIR jets are blueshifted to the southwest and redshifted to the northeast (Hayashi & Pyo 2009), the southwestern side of the disk and envelope must be the far side and the northeastern side the near side, assuming that the midplane of the disk and envelope is perpendicular to the axis of the jets. Correspondingly, the southwestern redshifted component would then be located on the far side and the northeastern blueshifted component on the near side, suggesting the outward radial motion on the plane. In the $^{13}$CO P–V diagram along the minor axis, both RED1 and RED2 and their decelerated velocity structures (red and purple dashed lines) are identified. These results indicate that the envelope is being dissipated due to the interaction with the redshifted outflowing gas driven from L1551 IRS 5. We will further discuss this dispersing motion of the envelope with the combined SMA+ASTE images of the C$^{18}$O emission below.

3.3. Spatial and Velocity Structures of the Inner Envelope and CBD Traced by the SMA+ASTE C$^{18}$O (3–2) Image Cube

Figure 9 compares moment 0 maps of the ASTE, SMA, and the combined SMA+ASTE image cubes of the C$^{18}$O (3–2) line in L1551 NE. While the ASTE image exhibits an extended
envelope structure as described in the last subsection, the SMA image shows the central smaller structure with its position angle (\( \sim 1000 \) AU \( \times 800 \) AU) consistent with that of the Keplerian CBD (Takakuwa et al. 2013). Combining these two images shows that the central structure found by the SMA observations is embedded in the more extended envelope.

Figure 10 shows velocity channel maps of the SMA+ASTE image cube of the C\(^{18}\)O (3–2) line. In the highly blueshifted (\( V_{\text{LSR}} = 4.2–6.1 \) km/s\(^{-1}\)) and redshifted (7.5–9.2 km/s\(^{-1}\)) velocities, compact C\(^{18}\)O emission located to the north and south of the protostellar binary are seen, respectively. These compact components trace the Keplerian CBD as we already discussed in our previous papers (Takakuwa et al. 2012, 2013, 2014). The extended envelope component appears in the lower velocity range (6.1–8.2 km/s\(^{-1}\)). In the blueshifted velocity range of 6.3–6.6 km/s\(^{-1}\), the extended C\(^{18}\)O emission is located predominantly to the eastern side of the protostellar binary, whereas in the redshifted velocity range of 7.5–8.2 km/s\(^{-1}\) to the western side. Thus, there is a velocity gradient along the east (blue) to west (red) direction in the envelope, which is also identified in the ASTE-only C\(^{18}\)O image cube as discussed in the last subsection. In the lower velocity region (6.6–7.4 km/s\(^{-1}\)) the envelope emission extends over the entire region.

To highlight these velocity structures in the SMA+ASTE image cube, we integrated the velocity channel maps over the high-velocity, middle-velocity, and the low-velocity blueshifted and redshifted regions, and the resultant images are shown in Figure 11. In the high-velocity region, compact blueshifted and redshifted C\(^{18}\)O emission located to the north and south of the
protostellar binary, which originates from the Keplerian CBD, are seen. In the middle-velocity region, as well as the central disk component, an extended envelope component, with the blue-shifted emission located predominantly to the east and the redshifted emission to the west, is seen. As we discussed in the last subsection, one interpretation of this velocity structure is the dispersing gas motion in the flattened envelope. In the low-velocity region, both the blueshifted and redshifted emission spread over almost the entire field of view. We note, however, that the blueshifted and redshifted emission peaks in the central compact emission are located slightly to the west and east of the protostellar binary, respectively. The sense of this velocity structure is opposite to that of the extended envelope seen in the middle-velocity range. This velocity structure is also seen in the SMA-only image cube and the centroid velocity of the envelope and the red and purple dashed lines delineate that of RED1 and RED2, respectively.

Figure 12 (left) shows the P–V diagrams of the combined SMA+ASTE C18O image cube with our toy model below.

4. ANALYSES

4.1. Toy Model for the Combined SMA+ASTE Image Cube

The combined SMA+ASTE C18O image cube reveals a sign of an outer dispersing envelope motion, possible inner infalling motion, and Keplerian rotation in the central CBD. To interpret...
these results quantitatively, we constructed a toy model of the envelope and disk assuming that the disk and envelope are geometrically thin and co-planar. Our model is essentially the same as that by Takakuwa et al. (2013), which reproduces the velocity structures of the SMA-only image cube, but now the outer dispersing envelope component is added to reproduce the velocity structure of the extended envelope component traced by ASTE. As a model moment 0 map, we adopted a combination of two two-dimensional (2D) Gaussians, which are derived from the Gaussian fitting to the observed SMA + ASTE moment 0 map (Figure 9, bottom right). The velocity structures in the inner component traced by the SMA are described as

$$v_{\text{rot}}(r) = 0 \text{ and } v_{\text{rad}}(r) = v_{\text{inf}} \text{ for } r > r_{\text{kep}},$$

(2b)

where $r$ is the radius, $G$ the gravitational constant, $M_*$ the mass of the protostellar binary, $v_{\text{rot}}(r)$ and $v_{\text{rad}}(r)$ are the rotational and radial velocities, respectively, $r_{\text{kep}}$ the outermost radius of the Keplerian rotation, and $v_{\text{inf}}$ an adopted constant infall velocity beyond $r_{\text{kep}}$. As discussed by Takakuwa et al. (2013), we adopt $M_* = 0.8 M_{\odot}$, $r_{\text{kep}} = 300$ AU, and $v_{\text{inf}} = -0.6$ km s$^{-1}$, and the disk inclination angle $i = 62^\circ$. The velocity structure of the outer envelope traced by ASTE is expressed as

$$v_{\text{rot}}(r) = 0 \text{ and } v_{\text{rad}}(r) = v_{\text{disp}} \text{ for } r > r_{\text{disp}},$$

(3)

where $r_{\text{disp}}$ and $v_{\text{disp}}$ are the innermost radius of the dispersing envelope and the dispersing velocity, respectively. $r_{\text{disp}} = 700$ AU is adopted, inferred from the comparison between the

\[v_{\text{rot}}(r) = \sqrt{\frac{GM_*}{r}} \text{ and } v_{\text{rad}}(r) = 0 \text{ for } r \leq r_{\text{kep}}, \quad (2a)\]
The dispersing velocity along the dispersion centroid velocity is incorporated. The internal velocity from that of the CBD, and in our model this offset of the SMA-only and SMA+ASTE velocity channel maps of the C$^{18}$O (3–2) line in L1551 NE. Contour levels start from 2σ in steps of 2σ until 10σ, and then in steps of 4σ (1σ = 0.598 K). Symbols are the same as those in Figure 9.

Figure 10. SMA+ASTE velocity channel maps of the C$^{18}$O (3–2) line in L1551 NE. Contour levels start from 2σ in steps of 2σ until 10σ, and then in steps of 4σ (1σ = 0.598 K). Symbols are the same as those in Figure 9.

SMA-only and SMA+ASTE moment 0 maps. $v_{\text{disp}}$ can be roughly estimated from the velocity gradient seen in the combined $P$–$V$ diagram along the minor axis as shown in Figure 12. The velocity shift of the emission ridge of the envelope across the minor axis is $\sim 0.5$ km s$^{-1}$, centered on the centroid velocity of 6.7 km s$^{-1}$, and at an inclination of $i \sim 62^\circ$ the dispersing velocity along the flattened envelope is $v_{\text{disp}} \sim (0.5$ km s$^{-1}/2)/\sin 62^\circ \sim 0.3$ km s$^{-1}$. Note that the centroid velocity of the envelope component is offset by $\sim -0.2$ km s$^{-1}$ from that of the CBD, and in our model this offset of the centroid velocity is incorporated. The internal velocity dispersion $\sigma_{\text{gas}} = 0.4$ km s$^{-1}$, which reproduces the velocity channel maps of the central CBD (Takakuwa et al. 2012), is adopted throughout the entire components.

Figure 13 shows the velocity channel maps of our toy model. In the high-velocity blueshifted (4.6–5.7 km s$^{-1}$) and redshifted ranges (7.7–9.2 km s$^{-1}$), the features of the Keplerian CBD are seen. In the blueshifted range of 5.9–6.3 km s$^{-1}$, the envelope component is located to the east of the protostellar binary while in the redshifted range of 7.2–7.5 km s$^{-1}$ to the west, reflecting the dispersing motion in the envelope. In the lower velocity range (6.4–7.0 km s$^{-1}$), the envelope component is extended in both the eastern and western sides, but the east (red)–west (blue) velocity gradient arising from the infalling motion in the central component is evident. These characteristics reproduce the primary features of the observed SMA+ASTE C$^{18}$O velocity channel maps in L1551 NE (Figures 10, 11). Figure 12 (right) shows the $P$–$V$ diagrams of our toy model along the major and minor axes. The model $P$–Vs can reproduce primary features of the observed $P$–Vs, such as the high-velocity component arising from the Keplerian disk, and the extended envelope component which shows a velocity gradient along the minor axis reflecting the dispersing motion, but no rotation along the major axis. These results show that the observed SMA+ASTE C$^{18}$O image cube in L1551 NE can be understood with three distinct velocity components; a central Keplerian CBD at a radius of $\lesssim 300$ AU, a possible infalling region at 300 AU $< r < 500$ AU, and an outer dispersing envelope with a dispersing velocity of $\sim 0.3$ km s$^{-1}$ at $r \gtrsim 500$ AU.

4.2. Physical Properties of the Gas Components
Identified with ASTE

Our ASTE mapping observations of the L1551 NE region have revealed three distinct gas components; i.e., ENV, RED1, and RED2. ENV is the component of the protostellar envelope surrounding the protostellar binary system L1551 NE, and exhibits the dispersing gas motion as discussed above. RED1 and 2 are most likely the redshifted outflow components driven from L1551 IRS 5, which are interacting with ENV.

To discuss the interaction between ENV and RED1 and RED2 quantitatively, the physical parameters of these components were estimated as follows. First, the moment 0 map of each component was made in the relevant tracers and the velocity ranges listed in Table 2. As shown above, ENV is most clearly identified in the C$^{18}$O (3–2) emission, and RED2 in the $^{13}$CO (3–2) emission. We adopt the CS (7–6) emission to deduce the physical condition of RED1, because in the CS emission RED1 can be identified as a distinct gas component most easily, and the submillimeter CS emission must trace higher temperature gas associated with outflows. We also note
that it is not straightforward to separate RED2 in the 3D space from the other lower velocity components. Here we identified RED2 as the $^{13}$CO emission component in the highest redshifted velocity range of $9.47 \pm 12.53 \, \text{km} \, \text{s}^{-1}$, since in this velocity range RED2 is a distinct highest redshifted component seen primarily in the $^{13}$CO emission. After making the moment 0 maps of these distinct components, 2D Gaussian fittings to the moment 0 maps were performed to derive the central positions, beam-deconvolved sizes along the major and minor axes, and the total fluxes. For ENV, a single 2D Gaussian fitting to the moment 0 map did not provide a satisfactory fit. Thus, for ENV two-components, 2D Gaussian fitting was performed, and the position was defined as the peak position of the central Gaussian component, while the size was defined as the size of the outer Gaussian component. The line widths of these components ($\Delta \nu$) were derived from the FWHM values of the relevant spectra toward the central positions. Projected flow velocities of RED1 and RED2, $v_{\text{flow}}$, were defined as the mean velocity at the center of the components with respect to the velocity of ENV ($\sim 6.7 \, \text{km} \, \text{s}^{-1}$).

Mases of the components ($M_{\text{LTE}}$) were derived from the total fluxes, on the assumption of the LTE condition, optically thin emission, and the molecular abundances of $X_{\text{LTE}} = 1.7 \times 10^{-7}$ (Crapsi et al. 2004), $X_{\text{LTE}} / X_{\text{LTE}} = 7.7$ (Wilson & Rood 1994), and $X_{\text{LTE}} = 6.8 \times 10^{-10}$ (Jørgensen et al. 2004). Since the peak brightness temperature ($T_{\text{peak}}$) of the $^{13}$CO emission toward the protobinary position exceeds $3.4 \, \text{K}$, the excitation temperature ($T_{\text{ex}}$) must exceed $9.0 \, \text{K}$ as $T_{\text{ex}} = T_{\text{peak}}$, $T_{\text{peak}}$ must be higher than $T_{\text{ex}}$, On the other hand, to excite the submillimeter CS (7–6) emission, a gas temperature as high as $\sim 60 \, \text{K}$ is required (Takakuwa et al. 2007a; Takakuwa & Kamazaki 2011). Thus, $T_{\text{ex}} = 10–60 \, \text{K}$ is assumed as a probable range of $T_{\text{ex}}$. Virial masses of the components ($M_{\text{vir}}$) were derived as

$$M_{\text{vir}} = \frac{5DC_{\text{eff}}^2}{2G},$$

where

$$C_{\text{eff}}^2 = \frac{\Delta \nu^2}{8 \ln 2}.$$  

In the above expressions, $D$ denotes the geometrical mean of the sizes along the major and minor axes of the components, and $C_{\text{eff}}$ the effective sound speed of gas. The isotropic velocity dispersion inside the components is assumed. For RED1 and RED2, the sizes ($\sim 4000 \, \text{AU}$) are as small as the beam size ($\sim 3200 \, \text{AU}$), and thus the line widths derived from the central spectra represent the average velocity dispersions. For ENV, there is no discernible spatial variation of the $^{13}$CO line width as shown in the $P$–$V$ diagrams (Figures 7, 8), except for that arising from the central disk. Thus, the assumption of the isotropic velocity dispersion inside these components is probably valid.

Moments ($\equiv p$), internal gas energies ($\equiv E_{\text{int}}$), and kinetic energies ($\equiv E_{\text{kin}}$) of the components were derived as

$$p_{\text{RED1,2}} = M_{\text{LTE}} v_{\text{flow}},$$

$$p_{\text{ENV}} = M_{\text{LTE}} v_{\text{disp}},$$
Table 2 summarizes these derived physical parameters. The size (\(\sim 20,000\) AU) and LTE mass (\(\sim 1–3\) \(M_\odot\)) of ENV are typical of protostellar envelopes (André et al. 2000; Myers et al. 2000; Takakuwa et al. 2003). The virial mass of ENV is comparable to or slightly larger than the LTE mass plus the central protobinary mass. From the comparison between the virial and LTE masses, it is not straightforward to ascertain whether or not ENV is gravitationally bound. On the other
hand, the identification of the dispersing gas motion in ENV implies that ENV is gravitationally unbound. The outflow components of RED1 and 2 are characterized with their compact sizes (\( \lesssim 4000 \text{ AU} \)) and wide line widths (\( \sim 1–2 \text{ km s}^{-1} \)). The LTE masses of the outflow components are likely lower than the corresponding virial masses, although for RED1 only the upper limit of the virial mass is obtained. These results indicate that RED1 and 2 are not gravitationally bound gas condensations, consistent with our interpretation that RED1 and 2 are outflowing gas components driven from L1551 IRS 5. The summed flow momentum of RED1 and 2 is comparable to that of the momentum of the dispersing motion of ENV. Furthermore, the net internal + kinetic and internal energies of these outflow components are comparable to those of ENV, suggesting that the outflow collisions can enforce significant dynamical impacts on the envelope. A natural interpretation of these results is that the protostellar envelope in L1551 NE is being disrupted through the interaction with the outflows driven from L1551 IRS 5. Figure 14 (bottom) shows a schematic, inferred configuration of the L1551 region viewed from the north, in parallel with the SCUBA 850 \( \mu \text{m} \) dust continuum image (Moriarty-Schieven et al. 2006) as a representative projected image onto the sky plane (top). In the SCUBA image a torus-like continuum feature connecting the envelopes around L1551 IRS 5 and NE is seen as delineated with a dashed green curve. This feature is drawn schematically in the bottom as the northernmost feature. Since the envelope around L1551 NE is interacting with the redshifted outflow components driven from L1551 IRS 5 (RED1 and 2), the location of L1551 NE must be backward with respect to the location of L1551 IRS 5 along the line of sight. As already described, the western side of the flattened envelope around L1551 NE is the far side and the eastern side is the near side. Thus, the blueshifted emission to the east and the redshifted emission to the west are interpreted as the dispersing gas motion in the flattened envelope.

5. DISCUSSION

5.1. Dispersing Envelope around the CBD in L1551 NE

Our new ASTE observations and combining the ASTE data with our previous SMA data in L1551 NE have revealed that the protostellar envelope around the Keplerian CBD is being dispersed. The dispersing envelope does not show any rotating gas motion in contrast with the Keplerian rotation in the CBD, and the centroid velocity of the envelope is \( \sim 0.2 \text{ km s}^{-1} \) blueshifted with respect to that of CBD. These results indicate that the protostellar envelope is kinematically distinct from the central CBD. The outflow components from L1551 IRS 5, as seen most prominently in the submillimeter CS (7–6) line (RED1) and the high-velocity redshifted \(^{13}\text{CO} (3–2)\) line (RED2), appear to collide and interact with the protostellar envelope. The net momentum and kinetic and internal energies of these outflow components are comparable to those of ENV, suggesting that the outflow collisions can enforce significant dynamical impacts on the envelope.
### Table 2

Physical Properties of the Gas Components in L1551 NE Identified with ASTE

| Component | Tracer     | R.A.  | Decl. | \( V_{\text{LSR}} \) (km s\(^{-1}\)) | \( \text{Size} \) (AU) | \( \Delta v \) (km s\(^{-1}\)) | \( v_{\text{flow}} \) (km s\(^{-1}\)) | \( M_{\text{LTE}} \) (\( M_{\text{Ec}} \)) | \( M_{\text{vir}} \) (\( M_{\text{Ec}} \) km s\(^{-1}\)) | \( \rho \) (\( \times 10^{42} \) erg) | \( E_{\text{int}} \) (\( \times 10^{42} \) erg) | \( E_{\text{kin}} \) (\( \times 10^{42} \) erg) |
|-----------|------------|-------|-------|--------------------------------------|------------------------|---------------------------------|---------------------------------|--------------------------------|---------------------------------|--------------------------------|--------------------------------|--------------------------------|
| ENV       | C\(^{13}\)O (3–2) | 04 31 44.4 | 18 08 36.4 | 5.31–8.15 | 22100 \( \times \) 18200 | 0.72 | \( \cdots \) | 1.3–3.1 | 5.3 | 0.38–0.93 | 3.5–8.7 | 1.14–2.78 |
| RED1      | CS (7–6)  | 04 31 42.0 | 18 08 06.0 | 8.04–9.13 | \(<4000\) | 0.97 | 1.9 | 0.02–0.83 | \(<1.9\) | 0.039–1.574 | 0.10–4.23 | 0.73–29.74 |
| RED2\(^e\) | \(^{13}\)CO (3–2) | 04 31 42.8 | 18 08 35.0 | 9.47–12.53 | 4300 \( \times \) 4000 | 2.0 | 3.5 | 0.02–0.05 | 8.4 | 0.069–0.169 | 0.42–1.04 | 2.4–5.9 |

**Notes.**

\( ^{a} \) Derived from 2D Gaussian fittings to the moment 0 maps of the individual components. For ENV, two-components, 2D Gaussian fitting is performed, and the position is defined as the peak position of the central Gaussian component, while the size is defined as the size of the outer Gaussian component.

\( ^{b} \) FWHM line widths of the spectra toward the center of the components.

\( ^{c} \) Mean velocity at the center of the components minus the velocity of the envelope component (=6.7 km s\(^{-1}\)).

\( ^{d} \) See the text for details.

\( ^{e} \) It is not straightforward to unambiguously separate RED2 from the other lower velocity components in the \(^{13}\)CO emission. Here RED2 is defined from the isolated component in the velocity higher than 9.47 km s\(^{-1}\).
formation of the protostellar binary system L1551 NE has initiated before the arrival of the IRS 5 outflows, because at present the protostellar envelope is kinematically distinct and thus physically detached from the CBD and the protostellar binary system. The similar binary masses (∼0.8 M☉ in L1551 NE and ∼0.5 M☉ in IRS 5), envelope masses (∼1 M☉), and the bolometric temperatures (Tbol ∼ 90 K) indicate that both L1551 IRS 5 and NE were born at similar times. After their birth, both L1551 NE and IRS 5 grow simultaneously. The angular separation between L1551 IRS 5 and NE is ∼2.5′, and assuming the transverse velocity of the outflows driven from L1551 IRS 5 is ∼10 km s⁻¹ (Moriarty-Schieven et al. 2006; Stojimirović et al. 2006; Wu et al. 2009), the transverse time for the IRS 5 outflow to reach the L1551 NE location is ∼10⁴ years. This timescale is approximately consistent with the estimated age of L1551 NE of (0.6–5.0) × 10⁴ years (Motte & André 2001). After the outflows from L1551 IRS 5 have arrived at the protostellar envelope around L1551 NE, the outflows start disrupting the envelope through the interactions. The possible infalling motion in the inner envelope found with the SMA may be a remnant gas motion before the initiation of the interactions with the IRS 5 outflows. Such a remnant infalling gas motion embedded in the dispersing envelope has also been identified in a T-Tauri star DG Tauri (Kitamura et al. 1996).

The envelope dispersion via the interactions with the IRS 5 outflows will impact the final fates of the protostellar binary system of L1551 NE significantly, as will be discussed in the next subsection.

5.2. Implication of Envelope Dispersion for Binary Growth

Binary stars with primary masses comparable to that of the Sun show a wide range of the binary mass ratios, and the distribution of the mass ratio (≡q) is essentially flat from q ∼ 0.1–1 (Raghavan et al. 2010; Goodwin 2013). Physical mechanisms to reproduce such a wide range of binary mass ratios have been controversial, and gas accretion in the CBDs onto the protostellar binaries has been discussed as a mechanism to set the final binary mass ratios. SPH simulations of circumbinary accretion show that the majority of materials accrete onto the secondary, because the secondary orbits further from the center of mass of the binary and thus sweeps more material in the CBD than the primary (Bate 1997, 2000; Bate & Bonnell 1997). Our 3D AMR hydrodynamic simulation to reproduce the ALMA results of the CBD in L1551 NE also shows that the secondary (Source B) accretes more than the primary (Source A; Takakuwa et al. 2014). On the other hand, high-resolution grid-based simulations by Ochi et al. (2005) and Hanawa et al. (2010) show that primaries accrete more than secondaries. The latest SPH simulations demonstrate that flows from the secondary to the primary within the Roche lobes are a sensitive function of gas temperatures, and in the case of high temperatures the primary accretes more than the secondary, and vice versa (Young et al. 2015).

Our ASTE observations of an archetypal protostellar binary L1551 NE imply that dispersion of protostellar envelopes, which replenish CBDs with fresh materials, also needs to be taken into account as a physical mechanism to set the binary masses and the ratios. The present masses of Sources A and B in L1551 NE are estimated to be ∼0.67 M☉ and ∼0.13 M☉, respectively, and the mass of the CBD ∼0.026 M☉ (Takakuwa et al. 2012). The mass of the possible infalling component...
around the CBD is even smaller (∼0.0023 $M_\odot$) (Takakuwa et al. 2013). Thus, even if all the amount of the material in the CBD plus the infalling component is accreted onto Source B, the mass ratio does not change much (from 0.19 to 0.24). Replenishment of the material to the CBD from the surrounding envelope is required to significantly change the mass and the mass ratio of the protostellar binary system. Our ASTE observations show that the envelope is being dispersed, however, and that further replenishment of materials from the envelope to the CBD will not be expected. Therefore, even though L1551 NE is a Class I protostellar binary associated with the CBD and the protostellar envelope, the mass and the mass ratio have already been close to the final values. Physical processes before the start of the envelope dispersion through the interaction with the outflow driven from L1551 IRS 5, such as the fragmentation of the initial pseudo-disk and subsequent accretion from the CBD and the envelope, must be responsible to set the mass and mass ratio of the binary system.

Our ASTE observations of L1551 NE indicate that dispersion of natal envelopes surrounding the protostellar binary systems is one of the key physical phenomena to stop the growth of the binary and to determine the final masses and the mass ratios of the binary. As described in the last subsection, the interactions between protostellar envelopes and outflows, which cause the envelope dissipation, are ubiquitous. Systematic studies of dispersion of envelopes surrounding the protostellar binaries with various masses and mass ratios are intriguing to understand the physical mechanism to set the final binary mass ratios and the origin of the wide range of the binary mass ratios.

6. SUMMARY

We have conducted single-dish mapping observations of dense gas around an archetypal protostellar binary L1551 NE in the C$^{18}$O ($J = 3–2$), $^{13}$CO ($J = 3–2$), CS ($J = 7–6$), and the SO ($J_K = 7_2–6_2$) lines with ASTE. We have also combined the ASTE interferometric data in the C$^{18}$O line with the interferometric data taken with the SMA. The main results are summarized below.

1. All four molecular lines are detected toward the protostellar position, with multiple and/or non-Gaussian spectral shapes. In particular, the C$^{18}$O spectrum consists of a narrow ($\Delta v \sim 0.7$ km s$^{-1}$) component with a central velocity of $V_{LSR} \sim 6.7$ km s$^{-1}$ and a wide ($\Delta v \sim 2.2$ km s$^{-1}$) component with a central velocity of $V_{LSR} \sim 6.9$ km s$^{-1}$. The wide component originates from the compact CBD, while the narrow component from the extended protostellar envelope.

2. The C$^{18}$O map in L1551 NE primarily traces a ∼20,000 AU scale protostellar envelope (ENV), elongated along the northwest to southeast direction, approximately parallel to the major axis of the central CBD. Velocity channel maps of the C$^{18}$O line show that the blueshifted ($V_{LSR} \sim 6.2–6.7$ km s$^{-1}$) emission is located to the northeast while the redshifted emission ($V_{LSR} \sim 6.7–8.0$ km s$^{-1}$) to the southwest; i.e., a velocity gradient of ENV along the minor axis, while there is no detectable velocity gradient along the major axis. The observed velocity gradient in ENV can be interpreted as a dispersing gas motion. Velocity channel maps of the high-speed redshifted ($V_{LSR} \gtrsim 8.0$ km s$^{-1}$) $^{13}$CO emission show two ∼4000 AU scale redshifted components to the ∼40$''$ southwest of the central protostar (RED1) and ∼20$''$ west (RED2). The submillimeter CS ($7–6$) emission selectively traces RED1, suggesting a high temperature in this high-velocity component. Both RED1 and RED2 exhibit similar velocity gradients such that the velocities become closer to the systemic velocity of ENV as the positions become closer to that of ENV. These high-velocity redshifted components most likely trace the outflow components driven from the neighboring protostellar source, L1551 IRS 5, which are colliding with ENV surrounding L1551 NE.

3. The combined ASTE+SMA map in the C$^{18}$O emission shows that the $r \sim 300$ AU scale CBD and $r \sim 700$ AU scale infalling component found in our previous SMA observations are surrounded by ENV with a slightly blueshifted velocity (∼0.2 km s$^{-1}$), ENV does not show any rotational motion but dispersing gas motion with an outward velocity of ∼0.3 km s$^{-1}$ in contrast to the inner gas components. These results indicate that ENV is kinematically distinct from the inner gas components.

4. The net momentum, kinetic, and internal energies of the redshifted outflow components driven from L1551 IRS 5 are comparable to those of ENV, suggesting that the outflow collisions can enforce significant dynamical impacts on ENV. Thus, the dispersing motion in ENV is likely caused by the interactions with the outflows driven from L1551 IRS 5.

5. Since ENV is being dispersed and the inner gas components do not have sufficient materials to alter the mass and mass ratio of the protostellar binary of L1551 NE, the current mass (∼0.8 $M_\odot$) and the mass ratio (∼0.19) are close to the final values, even though L1551 NE is a young Class I protostellar binary. Our ASTE+SMA observations of L1551 NE suggest that dispersion of natal protostellar envelopes which can replenish the CBDs with new materials is one of the important physical mechanisms to set the final binary mass ratios. The interactions with the outflows from L1551 IRS 5 are unlikely to trigger the binary formation in L1551 NE as suggested by previous studies, but suppress the further growth of the protostellar binary system.

We thank T. Matsumoto, T. Hanawa, J. Lim, N. Ohashi, and P.T.P. Ho for their fruitful discussions. We are grateful to S. Ohashi for his support during our ASTE observations. S.T. acknowledges a grant from the Ministry of Science and Technology (MOST) of Taiwan (MOST 102-2119-M-001-012-MY3) in support of this work. The ASTE telescope is operated by the National Astronomical Observatory of Japan (NAOJ).

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