HIGH-VELOCITY JETS AND SLOWLY ROTATING ENVELOPE IN B335

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Received 2009 February 9; accepted 2010 January 13; published 2010 February 2

ABSTRACT

We have performed detailed imaging and analyses of the Submillimeter Array observation in 230 GHz continuum, 12CO (2–1), 13CO (2–1), and C18O (2–1) emissions toward B335, an isolated and nearby (∼150 pc) Bok globule with an embedded Class 0 source ($L_{bol} \sim 1.5 L_\odot$). We report the first discovery of high-velocity ($V_{propagation} \sim 160 \text{ km s}^{-1}$) 12CO (2–1) jets with a size of $\sim 900 \times 1500 \text{ AU}$ along the east–west direction in B335. The estimated mass-loss rate ($\sim 2.3 \times 10^{-7} M_\odot \text{ yr}^{-1}$) and the momentum flux ($\sim 3.7 \times 10^{-5} M_\odot \text{ yr}^{-1} \text{ km s}^{-1}$) of the 12CO jets in B335 are one order of magnitude lower than those of other 12CO jets in more luminous sources such as HH 211 ($L_{bol} \sim 3.6 L_\odot$) and HH 212 ($L_{bol} \sim 14 L_\odot$). The weaker jet activity in B335 could be due to the lower active accretion onto the central protostar. The C18O emission shows a compact (∼1500 AU) condensation associated with the central protostar, and it likely traces the protostellar envelope around B335, as in the case of the 230 GHz continuum emission. The envelope exhibits a velocity gradient from the east (blueshifted) to west (redshifted) that can be interpreted as an infalling motion. The estimated central stellar mass, the mass infalling rate, and the accretion luminosity are $0.04 M_\odot$, $6.9 \times 10^{-6} M_\odot \text{ yr}^{-1}$, and $2.1 L_\odot$, respectively. On the other hand, there is no clear velocity gradient perpendicular to the outflow axis in the C18O envelope, suggesting little envelope rotation on a few hundred AU scale. The upper limits of the rotational velocity and specific angular momentum were estimated to be $0.04 \text{ km s}^{-1}$ and $7.0 \times 10^{-5} \text{ km s}^{-1} \text{ pc}$ at a radius of 370 AU, respectively. The specific angular momentum and the inferred Keplerian radius (∼6 AU) in B335 are one to two orders of magnitude smaller than those in other more-evolved sources. Possible scenarios to explain the lower specific angular momentum in B335 are discussed.

Key words: circumstellar matter – ISM: individual objects (B335) – ISM: molecules – stars: formation

1. INTRODUCTION

Dense-gas condensations ($\geq 10^4$–$10^5 \text{ cm}^{-3}$) in dark molecular clouds are the sites of low-mass star formation (Andre et al. 2000; Myers et al. 2000). Previous millimeter interferometric observations have revealed rotating and infalling gas motions in dense cores associated with known infrared sources, the so-called “protostellar envelopes” (Ohashi et al. 1996, 1997a, 1997b; Momose et al. 1998). Bipolar molecular outflows associated with protostellar envelopes have also been observed (Bachiller & Tafalla 1999). These molecular outflows are considered to be ambient material entrained by the jet, ejected from the vicinity of the central protostar. Eventually, the infall and the outflow terminate, and a newly born star surrounded by a circumstellar disk appears (Shu et al. 1987).

Details of the physical processes in protostellar envelopes and outflows, however, are still a matter of debate. For example, it is still unclear how the angular momentum of the rotating motion in envelopes is transferred from large to small radii (e.g., Goodman et al. 1993; Ohashi et al. 1997b), and how centrifugally supported disks with radii of a few hundreds AU often observed around young stars (e.g., Guilloteau et al. 1999; Guilloteau & Dutrey 1998; Qi et al. 2003) are formed in envelopes. In order to address these questions, observations of the rotating motion in a representative envelope, observed from large to small scales, and comparisons with other sources are required. On the other hand, the structure and kinematics of molecular outflows are different from source to source (Lee et al. 2000). In several sources high-velocity (HV; $> 100 \text{ km s}^{-1}$) collimated molecular jets have been found, while in other sources only slow outflow shells with wide opening angles are seen (Bachiller & Tafalla 1999; Arce et al. 2007). The mechanisms which produce this variety of outflows, and the relation of the mass ejection to the central mass accretion, are still controversial.

B335 is an isolated Bok globule associated with an embedded far-infrared source (IRAS 19347+0727; Keene et al. 1980, 1983). The distance to B335 has been recently re-estimated to be ∼150 pc (Stutz et al. 2008), and in this present paper, all the results referred from the literature have been corrected using this new estimate. The central source is a Class 0 source with a bolometric luminosity of 1.5 $L_\odot$ (Stutz et al. 2008) and a dust temperature of 31 K (Chandler & Sargent 1993). 12CO (1–0) and 13CO (1–0) line observations of B335 have unveiled the presence of a molecular outflow, both on ∼0.2 pc (Hirano et al. 1988; Cabrit et al. 1988; Moriarty-Schieven & Snell 1989) and ∼3000 AU scales (Hirano et al. 1992; Chandler & Sargent 1993). The outflow extends along the east–west direction, and shows a conical shape with an opening angle of ∼45° and an inclination angle of ∼10° from the plane of the sky. Along the outflow axis there are several HH objects (HH 119 A–F), whose proper motions moving away from the central source have been detected (Reipurth et al. 1992; Gåfalk & Oflofsson 2007). The dynamic timescale of the furthest HH object (HH 119 A) is ∼850 yr (Reipurth et al. 1992), and the propagation velocity reaches 140–170 km s$^{-1}$ (Gåfalk & Oflofsson 2007).

Single-dish observations of B335 have found asymmetric profiles in optically thick CS and H2CO lines, implying the presence of infalling motions in the envelope around B335 (Zhou et al. 1993; Choi et al. 1995). Direct interferometric imaging of the envelope around B335 in H13CO+ (1–0) and C18O (1–0) at an angular resolution of ∼6′ supports the presence of infalling motions on a 3000 AU scale (Saito et al. 2008; Arce et al. 1995).
The Submillimeter Array (SMA) is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics, and is funded by the Smithsonian Institute and the Academia Sinica.

of the CS (5–4) emission shows that the asymmetric line profiles are influenced severely by contamination from the outflow (Wilner et al. 2000). Recently, Choi (2007) has suggested that the asymmetric line profile in the H$_2$CO line arises from both the outflow and the infalling envelope. The envelope around B335 also exhibits a slow rotation at a radius of $\sim$20,000 AU (Frerking et al. 1987; Saito et al. 1999) and $\sim$1000 AU (Saito et al. 1999). The density distribution in the envelope around B335 shows an $r^{-1.5}$ dependence between radii of 60 and 3900 AU, while outside this region the radial dependence is $r^{-2}$ (Harvey et al. 2001, 2003a, 2003b), which is consistent with the inside-out collapse model (Shu 1977). B335 has also been observed in submillimeter molecular lines (Jørgensen et al. 2007; Takakuwa et al. 2007a).

These results indicate that B335 is a prototypical low-mass protostellar source suitable for detailed studies. The observations on 1000–4000 AU scales described above have revealed the core, infalling and rotating envelope, and outflow. In this present paper, we report detailed imaging and analyses of the Submillimeter Array (SMA)$^3$ observation of the region within 1500 AU in B335 at an angular resolution of $\sim$4$''$ to study the inner part of the outflow and the envelope. Through the comparison with previous observations of the envelope around B335 and those of other sources, we will discuss how the angular momentum of the rotating motion in envelopes is transferred. We will also compare the observed properties of the outflow in B335 with those of other sources associated with HV molecular jets, and discuss the relation of the outflow to the central mass-accretion processes.

2. OBSERVATION

The present observation of B335 was made as a part of a large SMA project (PROSAC; Jørgensen et al. 2007) on 2005 June 24 with the seven SMA antennas. Details of the SMA are described by Ho et al. (2004). The SMA is a double-sideband instrument with a 2 GHz bandwidth each. We observed 230 GHz continuum emission, $^{12}$CO (2–1; 230.5379700 GHz), $^{13}$CO (2–1; 220.3986765 GHz), and C$^{18}$O (2–1; 219.5603568 GHz) emissions in B335 simultaneously. The pointing center was $\alpha$(J2000) = 19h37m00.89s, $\delta$(J2000) = 7$''$.34'10.0", and the field of view was $\sim$55$''$ (8300 AU). The lengths of the projected baselines on the sky range from 5.5 to 53.5 k$''$, and our observation was insensitive to structures more extended than $\sim$4500 AU at the 10% level (Wilner & Welch 1994). The correlator configuration was set to assign 128 channels per one chunk with a 83.3 MHz bandwidth to the $^{12}$CO line, and 512 channels per chunk to the $^{13}$CO and C$^{18}$O lines, which results in a velocity resolution of 1.06, 0.26, and 0.28 km s$^{-1}$, respectively.

The passband calibrator was quasar 3C 279, and the flux calibrator was Callisto. Quasar 1749+096 (1.9 Jy) and quasar 2145+067 (2.5 Jy) were observed as gain calibrators. The MIRIAD software package was used to calibrate the data. The calibrated visibility data were Fourier-transformed and CLEANed with MIRIAD (Sault et al. 1995) to produce images. The observational parameters are summarized in Table 1. In order to improve the signal-to-noise ratio of the $^{12}$CO (2–1) data, we smoothed the data cube over two channels, and the noise level reduces to 100 mJy beam$^{-1}$.

3. RESULTS

The images of B335 in the 1.3 mm continuum, $^{12}$CO (2–1), $^{13}$CO (2–1), and the C$^{18}$O (2–1) emissions were first shown in the PROSAC paper (Jørgensen et al. 2007). In this paper, we present detailed results including velocity structures. Hereafter, the systemic velocity obtained from the single-dish results (Hirano et al. 1991; Evans et al. 2005), 8.3 km s$^{-1}$, is adopted, and all the velocities are shown as the relative velocity ($\Delta V$) to this systemic velocity.

3.1. 1.3 mm Continuum Emission

Figure 1 shows the 1.3 mm continuum image (contour) overlaid on the $^{12}$CO (2–1) moment 0 map (gray) in B335. The continuum emission shows an elongated structure along the north–south direction, plus two protrusions toward the northwest and southwest directions. The north–south elongation appears to be consistent with the previous single-dish result in the 1.3 mm continuum emission that shows an elongated feature with a size of $\sim$18,000 × 13,000 AU along the north–south direction (Motte & André 2001). As will be discussed in the next subsection, the $^{12}$CO emission most likely traces the molecular outflow along the east–west direction. Hence, the continuum emission is elongated almost perpendicularly to the east–west outflow, suggesting that the main component in the 1.3 mm continuum emission traces the circumstellar envelope around B335. On the other hand, the two protrusions abut upon the $^{12}$CO emission and delineate the rim of the outflow, which suggests that these components trace the wall of the cavity evacuated by the outflow.

By fitting a two-dimensional Gaussian to the continuum image above the 6$\sigma$ level, which excludes the northwest and southwest protrusions, we obtained the peak position of $\alpha$(J2000) = 19$^h$37$^m$00.93$^s$, $\delta$(J2000) = 7$^\circ$.34$^\prime$.09$^\prime\prime$.8, and hereafter we adopt this position as a position of the central protostellar source. The deconvolved size, position angle, and the total flux were estimated to be 4$''$.9 × 2$''$.3 (740 × 350 AU), 13$^\prime$., and 0.18 Jy, respectively. The 1.3 mm continuum flux recovered with the SMA corresponds to $\sim$25% of the integrated flux within a

| Table 1 |
| Summary of the Observational Parameters |
|---|
| **Line** | **Transition** | **Beam Size (P.A.)** | **Velocity Resolution (km s$^{-1}$)** | **Noise Level (mJy beam$^{-1}$)** | **Weighting** |
| $^{12}$CO | 2–1 | 3''.8 × 3''.3 (81:7) | 1.06 | 140 | Natural |
| $^{13}$CO | 2–1 | 4''.0 × 3''.4 (81:8) | 0.26 | 220 | Natural |
| C$^{18}$O | 2–1 | 3''.7 × 3''.2 (86:5) | 0.28 | 280 | Robust = 0.5 |
| Continuum | | | | | |
| 1.3 mm | ⋯ | 3''.9 × 3''.3 (81:7) | ⋯ | 2 | Natural |

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$^3$ The Submillimeter Array (SMA) is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics, and is funded by the Smithsonian Institute and the Academia Sinica.
We can estimate the mass of the main dusty component ($\equiv M$) as

$$M = \frac{F_\nu D^2}{\kappa_{230\text{ GHz}} B(T_{\text{dust}})},$$

(1)

where $F_\nu$ is the total flux, $D$ is the distance to the source, $T_{\text{dust}}$ is the dust temperature, and $B$ is the Planck function. On the assumption that the frequency ($\nu$) dependence of the dust mass opacity ($\equiv \kappa_\nu$) is $\kappa_\nu = 0.1 \times (\nu / \nu_0)^\beta$ (Beckwith et al. 1990) with $\beta = 1.2$ (Chandler & Sargent 1993), the mass opacity at 230 GHz ($\equiv \kappa_{230\text{ GHz}}$) was estimated to be 0.017 g cm$^{-2}$. The mass of the central compact component was estimated to be 0.027 $M_\odot$ at a dust temperature of 31 K (Chandler & Sargent 1993). Given the uncertainty of the missing flux, the estimated mass is consistent with the mass estimated from the 2.7 mm continuum emission by Owens Valley array observations (0.08 $M_\odot$; Chandler & Sargent 1993).

### 3.2. $^{12}$CO (2–1) Emission

Figure 2 shows the distribution of the $^{12}$CO (2–1) emission in B335 integrated over the following three different velocity ranges: HV ($\Delta V = -37.5$ to $-18.5$ & $17.5$ to $36.5$ km s$^{-1}$), middle velocity (MV; $\Delta V = -16.0$ to $-8.7$ & $6.9$ to $15.3$ km s$^{-1}$), and low velocity (LV; $\Delta V = -5.8$ to $-1.6$ and 0.6 to $4.8$ km s$^{-1}$). We detected the $^{12}$CO (2–1) emission at much higher velocity range ($\Delta V = -37.5$ to $36.5$ km s$^{-1}$) than the single-dish result ($\Delta V = -5.3$ to $5.7$ km s$^{-1}$; Hirano et al. 1991). In the LV range, the blueshifted and redshifted emissions show a V-shaped geometry opening toward the east and west, respectively, with its apex at the protostellar position. Similar but less significant blueshifted and redshifted V-shaped features are also seen on the other side, and hence the blueshifted and redshifted components are overlapped on each side. The maximum length, width, and opening angle of the V-shaped structures are $\sim 28''$ (4200 AU), $\sim 24''$ (3600 AU), and $\sim 60''$, respectively. From LV to HV, the morphology of the $^{12}$CO emission becomes more compact with less overlap between the blueshifted and redshifted components. In the HV range, neither the blueshifted nor the redshifted emission shows the V-shaped morphology, but both show compact condensations with a size of $\sim 1500 \times 900$ AU located near the protostar. The non-detection of the HV $^{12}$CO emission in the single-dish observation is probably due to the beam dilution effect, since the HV $^{12}$CO emission is compact. The peak position of these HV components is located within $\sim 2''$ ($\sim 300$ AU) of the protostar. On the assumption of an outflow inclination angle of 10$^\circ$ from the plane of the sky (Hirano et al. 1988), the mean propagation velocity of the HV $^{12}$CO emission reaches $\sim 160$ km s$^{-1}$, which is comparable to the velocity of the associated HH objects (140–170 km s$^{-1}$; Gålfalk & Olofsson 2007), and the dynamic timescale is estimated to be $\sim 45$ yr ($\sim 1500$ AU/160 km s$^{-1}$).

Figure 3 presents position–velocity ($P$–$V$) diagrams of the $^{12}$CO emission along the east–west direction (P.A. = 90$^\circ$) in B335. The $P$–$V$ diagram at a higher velocity resolution (2.1 km s$^{-1}$; Figure 3, left) exhibits a spatially extended (4200 $\times$ 3600 AU), narrow-velocity ($\sim 10$ km s$^{-1}$) feature of the LV component. The velocity structure of the LV component can be traced with a Hubble-like velocity law ($v = C \times r$) in a geometrically thin conical outflow shell with an opening angle of 60$^\circ$ and an inclination angle of 10$^\circ$, where the coefficient $C$ is found to be $1.2 \times 10^{-3}$ km s$^{-1}$ AU$^{-1}$ (orange dotted cross in Figure 3). These results suggest that the HV $^{12}$CO emission delineates the rim of the east–west outflow with a conical shape, and that the outflow axis is slightly tilted with its eastern part on the near side to us. Previous single-dish observations of B335 in $^{12}$CO (2–1 and 1–0) have found that there is an $\sim 0.2$ pc conical-shaped outflow along the east–west direction with an opening angle of $\sim 45^\circ$, and that the eastern outflow axis is tilted toward us by $\sim 10^\circ$ from the plane of the sky (e.g., Hirano et al. 1988, 1991). The Spitzer IRAC image in B335 shows a reflection nebula with its eastern lobe on the near side (Stutz et al. 2008). The single-dish and Spitzer results are consistent with our results, and the LV $^{12}$CO (2–1) emission observed with the SMA most likely traces the basement of the extended outflow in B335.

On the other hand, the $P$–$V$ diagram at a smoothed velocity resolution (4.2 km s$^{-1}$; Figure 3, right) with a better sensitivity shows that the kinematics of the HV $^{12}$CO is distinct from that of the LV component; the HV component exhibits a much wider velocity width ($\sim 20$ km s$^{-1}$) than the LV component, though the spatial extent of the HV component ($\sim 1500 \times 900$ AU) is much smaller than that of the LV component. Hence, the HV $^{12}$CO emission likely traces distinct outflow components from the LV outflow shell. On the assumption of local thermodynamic equilibrium (LTE) conditions and optically thin $^{12}$CO emission with an abundance of $10^{-4}$ (Ferriking et al. 1987; Lucas & Liszt 1998), and an excitation temperature of 50 K (Lee et al. 2007b), the column density at the peaks was estimated to be $6.7 \times 10^{19}$ cm$^{-2}$, and the gas masses of the redshifted and blueshifted HV components were estimated to be $2.3 \times 10^{-5}$ and $2.0 \times 10^{-5} M_\odot$, respectively. While the SMA $^{12}$CO observation misses 90% of the total flux observed with the James Clerk Maxwell Telescope (JCMT; Hirano et al. 1991) around the systemic velocity, the missing flux decreases to $\leq 30%$ at a relative velocity of more than 3 km s$^{-1}$. The flux from the HV component ($\Delta V \gtrsim 18$ km s$^{-1}$), which is compact and not detected by the JCMT, is mostly recovered with the present SMA.
Figure 2. Moment 0 maps of the $^{12}$CO (2–1) emission in B335 at different velocity ranges. For the HV range, contour levels are from $2\sigma$ to $6\sigma$ in steps of $2\sigma$, where $\sigma$ is $1.3$ K km s$^{-1}$. For the MV range, the contour levels are from $3\sigma$ to $15\sigma$ in steps of $3\sigma$, where $\sigma$ is $1.2$ K km s$^{-1}$. For the LV range, the contour levels are from $3\sigma$ to $71\sigma$ in steps of $4\sigma$, where $\sigma$ is $1.7$ K km s$^{-1}$. Crosses represent the position of the central source, and open circles represent the field of view. The filled ellipse at the bottom right corner in each panel shows the synthesized beam.

Figure 3. $P$–$V$ diagrams of the $^{12}$CO (2–1) emission along the outflow axis in B335, smoothed over the two (left panel) and four velocity (right panel) channels. Green dotted lines divide the $^{12}$CO emission into three different velocity components, and the blue and red lines show the velocity range of the HV components. Orange dotted crosses represent our simple model of the $^{12}$CO outflow shell. Contour levels are from $2\sigma$ in steps of $2\sigma$ until $10\sigma$, and then in steps of $6\sigma$, where $\sigma$ is $0.2$ K in the left panel and $0.1$ K in the right panel.

observation. We will discuss the origin of the HV components in Section 4.1 in more detail.

3.3. $^{13}$CO (2–1) Emission

Figure 4 presents moment 0 maps of the blueshifted ($\Delta V = -2.1$ to $0.0$ km s$^{-1}$) and redshifted ($\Delta V = 0.2$ to $1.9$ km s$^{-1}$) $^{13}$CO (2–1) emission in B335. The total velocity range of the $^{13}$CO emission ($\Delta V = -2.1$ to $1.9$ km s$^{-1}$) is within the velocity range of the $^{12}$CO LV component. We note that the absence of the $^{13}$CO counterpart to the $^{12}$CO HV component is likely due to the insufficient sensitivity of the observation. Both the blueshifted and redshifted $^{13}$CO emissions consist of central compact components with a size of $\sim 1000$ AU, and outer extensions, while the blueshifted emission is more intense than the redshifted emission. There are two redshifted “arms” extending toward the southeast and southwest directions and a blueshifted arm toward the southeast direction. These outer extensions, as well as the slight extensions to the northeast and
of law in a geometrically thin conical outflow shell on a size scale
velocity structure that can be explained as a Hubble-like velocity
lar velocity structure was also seen in the 12CO
similar morphology to that in the 13CO (2–1) emission, but the
absorption by foreground material.
respect to the blueshifted lobe, and hence will suffer more from
configuration, the redshifted outflow lobe is located behind with
the outflow shell than on the back side. In the outflow–envelope
emission could be due to less absorption on the front side of
more intense blueshifted emission compared to the redshifted
along the outflow axis, but on a size scale of
∼1500 AU, shown as the solid lines in Figure 5. A similar
velocity structure was also seen in the 12CO P−V diagram
along the outflow axis, but on a size scale of ∼2500 AU. The
more intense blueshifted emission compared to the redshifted
emission could be due to less absorption on the front side of the
outflow shell than on the back side. In the outflow–envelope
configuration, the redshifted outflow lobe is located behind with
respect to the blueshifted lobe, and hence will suffer more from
absorption by foreground material.
Assuming a 13CO abundance of 1.7 × 10^{-6} (Frerking et al.
1987), an excitation temperature of 20 K, and LTE and opti-
cally thin conditions, the gas masses traced by the blueshifted
and the redshifted 13CO emissions were estimated to be 1.9 ×
10^{-3} \, M_\odot and 3.2 × 10^{-3} \, M_\odot, respectively. The momenta of the
blueshifted and redshifted 13CO components were estimated to be
2.3 × 10^{-3} and 2.1 × 10^{-3} \, M_\odot \, km \, s^{-1}, respectively, using the
velocity channel maps \( P_{\text{13CO}} = \sum M_{\text{channel}} \times V_{\text{channel}} \).
Here, we assumed that the 13CO emission traces the same geo-
metrically thin conical shell as the LV 12CO component, and we
corrected for the inclination to estimate the propagation velo-
city. The estimated masses and momenta should be considered
as lower limits, since only ∼40% of the total 13CO (2–1) flux
obtained with the JCMT (Hirano et al. 1991) is recovered with
the present SMA observation.

3.4. C^{18}O (2–1) Emission

Figure 6 presents the moment 0 map of the C^{18}O (2–1)
emission integrated from \( \Delta V = -0.9 \, \text{km} \, \text{s}^{-1} \) to 0.8 \, \text{km} \, \text{s}^{-1}
in B335. In contrast to the 12CO and 13CO emissions, the
C^{18}O emission shows a ~1500 AU condensation with a single
peak slightly offset from the protostellar position by ~1\arcsec.
The condensation shows an almost spherical structure with north–
east, south–east, and weak south–west extensions, which is
consistent with the C^{18}O (1–0) map obtained using the Owens
Valley millimeter array (Chandler & Sargent 1993). Single-dish
observations of B335 in the C^{18}O (1–0) line show a ~36,000 ×
32,000 AU envelope with a mass of 2.4 \, M_\odot around the protostar
with an almost spherical structure (Saito et al. 1999).

Figure 7 shows the velocity channel maps of the C^{18}O (2–1)
emission overlaid with the 1.3 mm continuum emission (see
Figure 1). At \( \Delta V = -0.9 \, \text{km} \, \text{s}^{-1} \), weak C^{18}O emission elongated
along the north–south direction was detected to the east of the
protostellar position. At \( \Delta V = -0.6 \, \text{km} \, \text{s}^{-1} \), C^{18}O emission is
elongated along the outflow axis (P.A. = 90\arcdeg), and at \( \Delta V =
-0.3 \, \text{km} \, \text{s}^{-1} \), C^{18}O emission is elongated toward the south-east.
Around the systemic velocity \( \Delta V = 0.0 \, \text{to} \, 0.2 \, \text{km} \, \text{s}^{-1} \), C^{18}O
emission is elongated perpendicularly to the outflow axis, and
its distribution is similar to that of the 1.3 mm dust emission. At
a redshifted velocity of \( \Delta V = 0.5 \, \text{km} \, \text{s}^{-1} \), C^{18}O emission shows
a compact blob as well as a weak south–west extension with its
peak position slightly shifted to the west of the protostar. In the
channel maps, the peaks of the C^{18}O emission shift from east to
west of the protostar as the velocity changes from blueshifted
to redshifted.
Figure 6. Moment 0 map of the C$^{18}$O (2–1) emission in B335. The integrated velocity range is $\Delta V = -0.9$ to $0.8$ km s$^{-1}$. Contour levels are from $-2\sigma$ to $2\sigma$ in steps of $2\sigma$, where $\sigma$ is $0.5$ K km s$^{-1}$. A cross shows the position of the central source, and the filled ellipse at the bottom right corner shows the synthesized beam.

Figure 8 shows $P-V$ diagrams of the C$^{18}$O emission along (left panel) and across (right panel) the outflow axis passing through the central protostar. Along the outflow axis, there appears a velocity gradient: there are blueshifted and redshifted C$^{18}$O emission peaks at the east and west of the protostar, respectively. This velocity gradient could be due to the outflow. The $P-V$ diagram, however, does not show the X-shaped velocity structure seen in the 12CO and C$^{18}$O emissions. In fact, the model explaining the 12CO emission cannot be applied to the C$^{18}$O emission (bold solid lines in Figure 8, left). On the other hand, there is no clear velocity gradient seen in the C$^{18}$O $P-V$ diagram perpendicular to the outflow axis. We will discuss the origin and kinematics of the C$^{18}$O emission in Section 4.2.

The brightness ratio between the C$^{18}$O (2–1) and C$^{17}$O (2–1) emissions observed with the Caltech Submillimeter Observatory indicates that the C$^{18}$O (2–1) emission is optically thin ($\tau_{C^{18}O\ (2-1)} \sim 0.8$; Evans et al. 2005). Assuming LTE conditions, a C$^{18}$O abundance of $3 \times 10^{-7}$ (Frerking et al. 1987), and an excitation temperature of $30$ K (Chandler & Sargent 1993), we estimated the total gas mass of the C$^{18}$O condensation to be $5.2 \times 10^{-3}$ $M_\odot$ from the total C$^{18}$O integrated intensity ($\sim$9400 K km s$^{-1}$ over $\sim$140 arcsec$^2$). The derived gas mass is 6 times smaller than the mass estimated from the 1.3 mm dust continuum emission ($\sim$0.03 $M_\odot$), although the extent of the C$^{18}$O emission is approximately 2 times larger than that of the 1.3 mm dust continuum emission. This suggests that the C$^{18}$O abundance may be approximately one order of magnitude smaller than the value we assumed above, if the molecular gas and dust are well mixed and both the C$^{18}$O and 1.3 mm emissions trace the same structure. The lower C$^{18}$O abundance in the central region of the envelope could be due to the depletion of CO molecules onto dust grains. In fact, a similar degree of CO depletion has been suggested by modeling the single-dish line profiles of B335 (Evans et al. 2005). Although the missing flux of the SMA C$^{18}$O data is estimated to be 80% comparing to the single-dish flux of the C$^{18}$O (2–1) emission (Evans et al. 2005), the above discussion on the lower C$^{18}$O abundance is still valid because the C$^{18}$O and 1.3 mm dust continuum emissions miss a similar amount of flux.

4. DISCUSSION

4.1. High-velocity 12CO Component

Along with the V-shaped conical outflow shell, we have discovered compact ($\sim$1500 x 900 AU) HV ($V_{\text{propagation}} \sim 160$ km s$^{-1}$) 12CO (2–1) components in B335 with our SMA observation. Such an outflow configuration with collimated HV 12CO components plus low-velocity 12CO outflow shells is also seen in other low-mass protostellar sources associated with molecular jets such as HH 211 (Lee et al. 2006), HH 212 (Gueth & Guilloteau 1999), and L1448-mm (Bachiller et al. 1995), and has been explained by the jet-driven bow-shock model (Bachiller et al. 1995; Lee et al. 2006) and the wind-driven model (Shang 2007).

We estimated the activity of the HV 12CO jets in B335 with the method adopted by Lee et al. (2007a, 2007b) for the HH 211 jets. By assuming that the propagation velocity of the HV 12CO components is comparable to that in the other sources, in B335 there are several HH objects (HH 119 A-F) aligned along the outflow axis (Gål Falk & Olofsson 2007), which should trace bow shocks at the leading heads of the episodic mass ejection, and the propagation velocity of the HV 12CO components is consistent with that of these HH objects ($\sim$160 km s$^{-1}$). These facts suggest that the HV 12CO components found in B335 are most likely molecular jets and counterparts of the HV 12CO jets seen in HH 211, HH 212, and L1448-mm.

We estimated the activity of the HV 12CO jets in B335 with the method adopted by Lee et al. (2007a, 2007b) for the HH 211 and HH 212 jets. On the assumption that the transverse width of the 12CO jets in B335 is 300 AU as in the case of HH 211 (Lee et al. 2007b), the volume gas density in the 12CO jets (Frerking et al. 1987), and has been explained by the jet-driven bow-shock model (Bachiller et al. 1995; Lee et al. 2006) and the wind-driven model (Shang 2007). In Table 2, we compare the kinematical properties of the compact HV 12CO (2–1) components in B335 to those of the three 12CO jets mentioned above. The line width and the propagation velocity of the compact HV 12CO components in B335 are comparable to those in the other sources. In addition, in B335 there are several HH objects (HH 119 A-F) aligned along the outflow axis (Gål Falk & Olofsson 2007), which should trace bow shocks at the leading heads of the episodic mass ejection, and the propagation velocity of the HV 12CO components is consistent with that of these HH objects ($\sim$160 km s$^{-1}$). These facts suggest that the HV 12CO components found in B335 are most likely molecular jets and counterparts of the HV 12CO jets seen in HH 211, HH 212, and L1448-mm.

We estimated the activity of the HV 12CO jets in B335 with the method adopted by Lee et al. (2007a, 2007b) for the HH 211 and HH 212 jets. On the assumption that the transverse width of the 12CO jets in B335 is 300 AU as in the case of HH 211 (Lee et al. 2007b), the volume gas density in the 12CO jets ($\equiv n_{\text{jet}}$) was estimated to be $\sim 1.5 \times 10^4$ cm$^{-3}$ (from the column density of $\sim 6.7 \times 10^{19}$ cm$^{-2}$; see Section 3.2). By assuming that the jet morphology is cylindrical, the mass-loss rate ($M_{\text{loss}}$) can be derived as:

$$M_{\text{loss}} = \pi r^2 \rho \nu V_{\text{jet}} n_{\text{jet}} \mu,$$

where $r$ is the radius of the jet, $\rho$ is the gas density, $\nu$ is the mass flux, $V_{\text{jet}}$ is the jet speed, $n_{\text{jet}}$ is the number density of the jet, and $\mu$ is the mean molecular mass.

### Table 2

Comparison of Collimated High-velocity 12CO Emissions Among Different Sources

| Source | Transition | Inclination Angle (°) | Line Width (km s$^{-1}$) | Velocity (km s$^{-1}$) | References |
|--------|------------|----------------------|--------------------------|------------------------|------------|
| B335   | 2–1        | 10                   | 20                       | 160                    | 1, this paper |
| HH 212 | 2–1        | 4                    | 14                       | 120                    | 2, 3       |
|        | 3–2        | 14                   | 190                      | 4                      |            |
| HH 211 | 3–2        | 5                    | 15                       | 200                    | 5, 6       |
| L1448 mm | 1–0      | 21                   | 20                       | 200                    | 7, 8       |

Note.

a The velocities represent the propagation velocity estimated as $V_{\text{propagation}} / \sin(\text{inclination angle}).$

References. (1) Hirano et al. 1988; (2) Claussen et al. 1998; (3) Lee et al. 2006; (4) Lee et al. 2007a; (5) Lee et al. 2007b; (6) Lee et al. 2009; (7) Bachiller et al. 1995; (8) Girart & Acord 2001.
where $r$, $v_{\text{jet}}$, and $n_{\text{jet}}$ represent the radius, propagation velocity, and volume gas density in jets, respectively, and $\mu$ is the mean molecular weight. Then the mass-loss rate was estimated\(^4\) to be $2.3 \times 10^{-7} \, M_\odot \, \text{yr}^{-1}$, and the momentum flux ($\equiv F = \dot{M}_{\text{loss}} \times v_{\text{jet}}$) was estimated to be $3.7 \times 10^{-5} \, M_\odot \, \text{yr}^{-1} \, \text{km s}^{-1}$.

In Table 3, we compare the estimated jet activity in B335 with those in HH 211 and HH 212. The density, mass-loss rate, and momentum flux in B335 are one order of magnitude lower than

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\(^4\) If we estimate $\dot{M}_{\text{loss}}$ by $M_{\text{jet}}/T_{\text{dynamic}}$, the value becomes 3 times larger.
those in HH 212 and HH 211. In B335, thermal SiO emission, which is considered to be an excellent tracer of bow shocks in protostellar jets (Bachiller 1996), was not detected (Jørgensen et al. 2007), while intense SiO emission was found in HH 211 (e.g., Lee et al. 2007b), HH 212 (e.g., Lee et al. 2007a), and L1448-mm (e.g., Girart & Acorde 2001). Moreover, through high-J $^{13}$CO line observations in far-infrared, the temperature of the outflow in B335 was estimated to be ~350 K with an LVG model, and it is lower than that in the other protostellar jets, such as L1448-mm (~1200 K) and HH 211 (350–950 K; Giannini et al. 2001). In this paper, HH 211, HH 212, and L1448-mm, the $^{12}$CO jets conform to a chain of knots between the two successive extended bow shocks, while in B335 only one HV $^{12}$CO knot located close to the central protostar (~1500 AU) is found. These results suggest that the jet phenomena in B335 are less active than those in the other sources.

In Table 4, we compare the protostellar properties of B335 with those of the other driving sources of the jets. It is clear that the bolometric luminosity of B335 is lower than that of HH 212, 211, and L1448-mm, although their bolometric temperatures are similar. The ratio between the bolometric luminosity and the central stellar mass, which should be proportional to the mass-accretion rate in the central accretion disk, is more than 2–3 times lower in B335 than in the other sources. Hence, the lower mass-loss rate and the weaker jet activity in B335 compared to the other sources are likely to be linked with the lower mass-accretion rate in B335. We suggest that the jet activity is closely related to the properties of the central accretion process.

### 4.2. The Origin and Kinematics of the $^{18}$O Emission

As shown in Figure 7, the $^{18}$O emission at $\Delta V = 0.6$ and $0.3$ km s$^{-1}$ shows elongation toward the east and southeast directions, respectively, which is similar to that of the outflow observed in $^{12}$CO (2–1) and $^{13}$CO (2–1) emissions. On the other hand, at around the systemic velocity ($\Delta V = 0.0$ and 0.2 km s$^{-1}$), the $^{18}$O emission is elongated perpendicularly to the outflow axis. In addition, there is a velocity gradient in the $^{18}$O emission along the outflow axis at around the systemic velocity, while no clear velocity gradient is seen across the outflow axis. In order to study the origin and kinematics of the $^{18}$O emission, in Figure 9, we compare the $^{18}$O emission, integrated in four different velocity ranges, with the $^{13}$CO emission integrated in the same velocity ranges and with the 1.3 mm dust continuum emission. At around the systemic velocity ($\Delta V = 0.0$ and 0.2 km s$^{-1}$), both the blueshifted and redshifted $^{18}$O emissions show clear elongation perpendicular to the outflow axis and resemble the dust continuum emission in morphology. In contrast, the $^{13}$CO emission at the same velocity is elongated along the outflow axis, and is likely to trace the outflow. The highly blueshifted $^{18}$O emission ($\Delta V = -0.9$ to $-0.3$ km s$^{-1}$) shows elongation toward the southeast with a slight extension toward the northeast, and this morphology is similar to that of the $^{13}$CO emission at the same velocity. The highly redshifted $^{18}$O emission ($\Delta V = 0.5$ to 1.1 km s$^{-1}$) shows a central condensation elongated perpendicularly to the outflow axis with a weak extension toward the southeast. Although the $^{18}$O emission shows an extension similar to the $^{13}$CO outflow shells, the overall structure of the $^{18}$O central condensation is not similar to that of the $^{13}$CO outflow at the same velocity range. Therefore, the $^{18}$O emission (at least at around the systemic velocity and probably at the highly redshifted velocity) traces structures different from the outflow traced by the $^{13}$CO emission, and most likely traces the flattened molecular envelope perpendicular to the outflow axis. Such a flattened molecular envelope has often been observed around low-mass protostars (e.g., Ohashi et al. 1997a). Because the molecular outflow associated with B335 is aligned with the plane of sky closely, it is naturally expected for the flattened envelope to have an almost edge-on configuration and to show an elongated structure seen in channel maps.

Since the blueshifted and redshifted outflow emissions arise mostly from the east and west sides of the protostar, respectively,
the eastern lobe of the outflow is tilted toward us from the plane of the sky. Hence, the eastern part of the envelope is tilted away from us, while the western part of the envelope is tilted toward us from the plane of the sky. In this configuration, the eastern part of the envelope is the far side, while the western side is the near side. The flattened envelope shows a velocity gradient along its minor axis with the blueshifted emission on the far side and the redshifted emission on the near side. This suggests that the flattened envelope has an infalling motion toward the central protostar. In Figure 10, we show a schematic picture of the configuration of the outflow and the infalling flattened envelope described above. From the peak offset between the channels at $\Delta V = 0.0$ and $0.2$ km s$^{-1}$, where the $^{13}$CO emission most likely traces the flattened envelope, the velocity gradient along the minor axis was measured to be $3.7 \times 10^{-3}$ km s$^{-1}$ AU$^{-1}$. From this velocity gradient, the infall velocity was estimated to be $0.28$ km s$^{-1}$ at a radius of 440 AU on the assumption of an inclination angle of $10^\circ$. This infall velocity yields a central stellar mass of $0.02 M_\odot$ in the case of the free-fall motion.

On the other hand, there is no detectable velocity gradient between these two channels ($\Delta V = 0.0$ and $0.2$ km s$^{-1}$) across the outflow axis, suggesting no detectable rotation in the flattened envelope on a few hundred AU scale. Although there is no detectable rotation in the envelope on a few hundred AU scale, the flattened envelope could be produced by a magnetic field (e.g., Galli & Shu 1993). In addition, an outflow can sweep away a part of the material in the envelope along the outflow axis, making the shape of the envelope flattened. Two Class 0 sources, NGC 1333 IRAS 2A (Brinch et al. 2009) and IRAS 16293$-$2422 (Takakuwa et al. 2007b), show similar cases; their innermost envelopes showing disk-like structures also have no detectable rotation on a few hundred AU scale.

In order to study the kinematics of the envelope in more detail, we constructed a simple model of a geometrically thin infalling and rotating envelope with a Gaussian intensity distribution and compared it with the observation. Note that even though the actual envelope has a thickness, we use a model without thickness to make the model simpler. Although the Gaussian intensity distribution is an arbitrary choice, the choice of the intensity distribution does not affect main velocity structures. The radius of the model envelope was set to be 370 AU based on the semi-major axis of the 1.3 mm dust continuum emission (see Section 3.1). The inclination angle of the outflow (Hirano et al. 1988) was adopted as that of the envelope. The radial motion of the model envelope due to the dynamical infall is described as $v_r(r) = \sqrt{2GM_\star/r}$, where $M_\star$ is the mass of the central star, while its angular motion due to rotation is described as $v_\phi(r) \propto r^{-1}$ because of the angular momentum conservation. Based on the measurement of the infall velocity using the channel maps.
described above, the stellar mass was initially set to be 0.02 $M_\odot$. The rotational velocity was set to be 0.04 km s$^{-1}$ at $r = 370$ AU, which corresponds to the detection limit, because there is no detectable rotation. Then, we generated synthesized images of the model envelope with the same UV sampling as our SMA observation.

For the comparison between the model and the observation, we produced $P-V$ diagrams from both the model and observation as shown in Figure 11. Green contours in Figures 11(a) and (g) show the $P-V$ diagrams derived from the model. This simple model can reproduce the main feature of the $C^{18}$O $P-V$ diagrams both along and across the outflow axis. We note that there is a velocity difference in the redshifted peak between the model and the observation. In order to match the model redshifted peak with the observed peak, we need to adopt a higher stellar mass in the model. In the case of a model with a stellar mass of 0.04 $M_\odot$ as shown in Figures 11(b) and (h), the model redshifted peak better matches the observed peak. If we adopt an even higher stellar mass (0.08 $M_\odot$; Figures 11(c) and (i)), the model blueshifted peak would be offset from the observed peak due to the larger line width. On the other hand, if we set a higher rotational velocity such as $v_{\phi} = 0.16$ km s$^{-1}$ at $r = 370$ AU in the models (Figures 11(j)-(l)), there is a clear velocity gradient in the model $P-V$ diagrams across the outflow axis, different from the observation which show no detectable velocity gradient across the outflow axis. Therefore, the model with a stellar mass of 0.04 $M_\odot$ and a rotational velocity of 0.04 km s$^{-1}$ at a radius of 370 AU provides a $P-V$ diagram that matches the observation best. We note that there is a slight positional shift in the blueshifted peak between the model and observation in the $P-V$ diagram along the outflow axis. Although a higher inclination angle could provide a better match of the model blueshifted peak with the observed peak, the difference may be due to contamination of outflowing motions in the observation, since part of the blueshifted emission may arise from the outflow.

### 4.3. Infalling Motion in the Envelope

From our simple model of the infalling envelope (see Section 4.2), the infalling velocity in the envelope around B335 was estimated to be 0.31–0.44 km s$^{-1}$ at a radius of 370 AU, which corresponds to a central stellar mass ($\equiv M_*$) of 0.02–0.04 $M_\odot$. With an envelope mass ($\equiv M_{\text{env}}$) of 0.027 $M_\odot$ derived from the 1.3 mm continuum emission, the mass infalling rate...
been detected around the protostar in B335, which could suggest ejection and accretion. In addition, the \([\text{O} \text{d}]\) line emission has ejection and accretion. In addition, the \([\text{O} \text{d}]\) line emission has been detected in a number of protostellar sources, and are often linked to a sudden increase in the mass accretion (Arce et al. 2007). In fact, Dunham et al. (2008) and Enoch et al. (2009) have revealed that many protostellar sources show one order of magnitude lower bolometric luminosity than the accretion luminosity predicted from the steady mass-accretion model, and have proposed that the accretion is episodic and sources with lower bolometric luminosity than model predictions are probably in the quiescent stage. Direct observational comparisons between the accretion luminosity derived from the observed infalling motion in the envelopes and the bolometric luminosity also suggest non-steady mass accretion. In HL Tau (Lin et al. 1994; Hayashi et al. 1993), L1551 IRS 5 (Ohashi et al. 1996; Saito et al. 1996), and in IRAS 16293–2422 (Takakuwa et al. 2007b), the estimated accretion luminosities are an order of magnitude higher than the bolometric luminosities, and in HH 212 (Zinnecker et al. 1998; Lee et al. 2006), the accretion luminosity (~7 \(L_\odot\)) is lower than the bolometric luminosity (14 \(L_\odot\)). This mismatch could be reconciled by a picture similar to the FU- Ori phenomenon (Hartmann & Kenyon 1996) and episodic mass accretion. The protostar is surrounded by a disk, and outside of the disk there exists an infalling envelope. The material in the envelope keeps infalling onto the disk but not directly onto the surface of the protostar. In the “non-active” phase, most material in the disk does not accrete onto the surface of the protostar, and the jet ejection is also quiescent. Hence, the accretion luminosity derived from the mass infalling rate in the infalling envelope could be higher than the bolometric luminosity, as in the case of HL Tau, L1551 IRS5, and IRAS 16293–2422. When the disk becomes massive and unstable, the material accumulated in the disk starts falling onto the surface of the protostar, and then the powerful mass ejection also occurs (Hartmann & Kenyon 1996). This is the “active” phase, when the accretion luminosity estimated from the outer infalling envelope could be lower than the “real” accretion luminosity, as in the case of HH 212 associated with the clear HV jets. Our detection of HV molecular jets with a short dynamic timescale (~45 yr), and a possibly lower accretion luminosity than the bolometric luminosity in B335, imply a recent burst of mass ejection and accretion. In addition, the [O I] line emission has been detected around the protostar in B335, which could suggest the presence of shocks due to a recent ejection of the jets (Nisini et al. 1999). These results are consistent with the idea that B335 is in an “active” accretion phase.

4.4. Non-conserved Angular Momentum in B335

The infalling envelope traced by \(^{18}\text{O}\) (2–1) emission in B335 does not show any clear velocity gradient perpendicular to the outflow axis, suggesting an absence of rotational motion on the envelope at the 300 AU scale. The upper limit of the specific angular momentum was estimated to be \(7 \times 10^{-5}\) km s\(^{-1}\) pc (see Section 4.2), which corresponds to a rotational velocity of 0.04 km s\(^{-1}\) at a radius of 370 AU. Since the material within this radius is considered to be dynamically infalling (see Section 4.3), the specific angular momentum of the material within this radius is supposed to be conserved. If this is the case, the centrifugal force of the rotation becomes balanced with the gravitational force due to the central protostar with a mass of 0.04 \(M_\odot\) at a radius of ~6 AU, which can be considered an upper limit for the radius of the Keplerian rotating disk. The upper limit of the specific angular momentum on the small scale (~7 \(\times 10^{-5}\) km s\(^{-1}\) pc) is, however, much lower than the measured specific angular momenta at radii of 1000 AU (~5.4 \(\times 10^{-4}\) km s\(^{-1}\) pc) and 20,000 AU (~4.6 \(\times 10^{-3}\) km s\(^{-1}\) pc; Saito et al. 1999). If the angular momentum is conserved from large to small scales, the material falling from a radius of 20,000 AU should rotate at a velocity of 2.8 km s\(^{-1}\) at a radius of 370 AU, which is 70 times larger than the upper limit of the rotational velocity estimated using the present observation. These results show that the rotational motion in the envelope around B335 is spinning down toward the inner radii.

This decrease in the specific angular momentum from large to small scales has also been found in other protostellar sources and \(^3\text{H}\) \text{N}\) cores by Ohashi et al. (1997b) and Goodman et al. (1993). The specific angular momentum in B335 at a radius larger than 20,000 AU is similar to that of the \(^3\text{H}\) \text{N}\) cores; however, the specific angular momentum on the few hundred AU scale in B335 is one order of magnitude smaller than that in other protostellar sources (see Table 5). This lower specific angular momentum on the small scale could be explained by evolutionary effects as follows. A study of velocity gradients in \(^3\text{H}\) \text{N}\) cores by Goodman et al. (1993) has shown that the specific angular momentum is larger at a larger radius (i.e., \(J \propto r^{1.6}\)). If B335 is in an early phase of the inside-out collapse of such a dense core, the material in an outer region with a larger angular momentum has not yet fallen into the central region, and only the material at an inner radius with a smaller angular momentum has fallen in dynamically. Hence, the specific angular momentum on the few hundred AU scale in B335 could be still small.

To test this scenario, we estimated the size of the dynamical-observing region and the maximum amount of the specific angular momentum carried in by the dynamical infall. Based on single-dish observations of the envelope around B335 in \(^{18}\text{O}\) (1–0) emission by Saito et al. (1999) and the core rotation profile found by Goodman et al. (1993), we assumed that the initial condition of the core in B335 is a sphere with a rotation profile \(\propto r^{0.6}\), a density profile \(\propto r^{-2}\), a total mass of 2.4 \(M_\odot\), and a core radius of 20,000 AU. Our SMA observation shows that the total mass of the region within a radius of 370 AU is ~0.1 \(M_\odot\) (envelope + protostar). This amount of material was originally enclosed within a radius of 940 AU in the initial core. At this 940 AU radius, the initial core has a specific angular momentum of ~3.5 \(\times 10^{-5}\) km s\(^{-1}\) pc. Therefore, the angular momentum which has been carried in during the inside-out collapse is consistent with our upper limit for the angular momentum in the inner region. Moreover, the timescale of the propagation of the expansion wave to this 940 AU radius is ~2.2 \(\times 10^4\) years, on the assumption of the sound speed of 0.2 km s\(^{-1}\) (Shu 1977). This timescale is smaller than typical Class 0 lifetime (1.7 ± 0.3 \(\times 10^3\) yr; Enoch et al. 2009). Hence, the small angular momentum in the inner region in B335 can be explained by the early phase of the inside-out collapse, and the material with
larger angular momenta at the outer part has not yet fallen in and accumulated in the inner region.

For this scenario, we expect that as the expansion wave propagates outward, a larger amount of the angular momentum will be carried in and accumulated into the inner region, resulting in a larger radius of the Keplerian disk. In Table 5, we compare the evolution of the Keplerian radius from Classes 0 to II could be due to the transportation of the angular momentum inside the disk (Hartmann et al. 1998; Kitamura et al. 2002).

### Table 5

Keplerian Radius of the Protostellar Sources

| ID | Sources | Class | \( j \) (pc km s\(^{-1}\)) | \( r \) (AU) | Keplerian Radius (AU) | References |
|----|---------|-------|----------------|---------|----------------------|------------|
| 1  | GG Tau  | II    | \(3.5 \times 10^{-3}\) | 460     | 460                  | 1          |
| 2  | DM Tau  | II    | \(2.2 \times 10^{-3}\) | 630     | 630                  | 2          |
| 3  | HL Tau  | II    | \((6.5-6.8) \times 10^{-4}\) | 700     | 30-40                | 3, 4       |
| 4  | LkCa15  | II    | \(2.8 \times 10^{-3}\) | 430     | 430                  | 5          |
| 5  | L1527   | I     | \(4.9 \times 10^{-4}\) | 2000    | 110                  | 6          |
| 6  | L1551 IRS 5 | I     | \((8.2-10.0) \times 10^{-4}\) | 700-900 | 50-320               | 7, 8, 9    |
| 7  | IRS 63  | I     | \(8.8 \times 10^{-4}\) | 100     | 100                  | 10         |
| 8  | Elias 29 | I     | \(3.2 \times 10^{-3}\) | 200     | 200                  | 10         |
| 9  | HH 212  | 0     | \(6.7 \times 10^{-4}\) | 460     | 70                   | 11         |
| 10 | HH 211  | 0     | \(2.9 \times 10^{-4}\) | 80      | 80                   | 12         |
| 11 | B335    | 0     | \(7 \times 10^{-5}\) | 370     | 6                    | This paper |

**Notes.** \( j \) represents the specific angular momentum derived from disk or envelope rotation at the radius, \( r \). If the Keplerian disk has been observed in the sources, the Keplerian radius represents the outer radius of the disk. If the rotating-supported disk has not been found in the sources, the Keplerian radius is inferred from the envelope rotation and the estimated stellar mass.

**References.** (1) Guilloteau et al. 1999; (2) Guilloteau & Dutrey 1998; (3) Hayashi et al. 1993; (4) Lin et al. 1994; (5) Qi et al. 2003; (6) Ohashi et al. 1997a; (7) Momose et al. 1998; (8) Saito et al. 1996; (9) Takakuwa et al. 2004; (10) Lommen et al. 2008; (11) Lee et al. 2006; (12) Lee et al. 2009.

protostellar sources could be due to the efficiency of magnetic braking. Simulations have shown that angular momentum can be removed effectively during collapse with a strong magnetic field (Basu & Mouschovias 1994; Hennebelle & Fromang 2008; Mellon & Li 2008, 2009). With this Larson–Penston collapse scenario, it would be difficult to explain the increase of the Keplerian radius with evolution, since the majority of the material falls in at almost the same time. If this is the case, the evolution of the Keplerian radius from Classes 0 to II could be due to the transportation of the angular momentum inside the disk (Hartmann et al. 1998; Kitamura et al. 2002).

5. SUMMARY

We have performed detailed imaging and analyses of the SMA Observation of B335 in 1.3 mm continuum, \(^{12}\)CO (2–1), \(^{13}\)CO (2–1), and \(^{13}\)CO (2–1) emissions, taken as a part of our large low-mass star formation project, “PROSAC.”

1. In \(^{12}\)CO emission, we found two distinct outflow components associated with B335; one blueshifted (\(\Delta V = -5.8\) to \(-1.6\) km s\(^{-1}\)) and redshifted (\(\Delta V = 0.6\) to 4.8 km s\(^{-1}\)) V-shaped structure opening toward the east and west of the protostar, respectively, which probably delineates the conical-shaped outflow shell with the eastern side inclined slightly (\(-30^\circ\)) toward us, and the other is a compact (1500 \times 900 AU), HV blueshifted (\(\Delta V = -37.5\) to \(-18.5\) km s\(^{-1}\)) and redshifted (\(\Delta V = 17.5\) to 36.5 km s\(^{-1}\)) component to the east and west of the protostar, respectively. The mean propagation velocity (\(-160\) km s\(^{-1}\)) of the HV components is comparable to the velocity of the associated HH objects (140 to 170 km s\(^{-1}\)), and the HV components probably trace molecular jets driven by B335. The \(^{13}\)CO emission traces the low-velocity outflow shell.

2. The \(^{13}\)CO emission shows a compact (\(-1500\) AU) condensation with an east (blueshifted) to west (redshifted) velocity gradient. Around the systemic velocity (\(\Delta V = 0.0\) to 0.2 km s\(^{-1}\)), the \(^{13}\)CO emission shows a similar structure to that in the 1.3 mm continuum emission and elongation perpendicular to the direction of the associated outflow. Hence,
the C\textsuperscript{18}O emission probably traces the protostellar envelope around B335. The east–west velocity gradient can be interpreted as an infalling gas motion in the flattened disk-like envelope, while there is no clear velocity gradient along the north–south direction or sign of the rotation in the envelope on a few hundred AU scale. From our simple modeling of the infalling disk-like envelope, the central stellar mass and the mass inflaring rate were estimated to be \( \sim 0.02–0.04 \, M_\odot \) and \( \sim 4.8–6.9 \times 10^{-6} \, M_\odot \, \text{yr}^{-1} \), respectively, and the accretion luminosity was estimated to be \( \sim 0.7\text{–}2 \, L_\odot \). The upper limit of the specific angular momentum is estimated as \( \sim 7 \times 10^{-5} \, \text{km s}^{-1} \, \text{pc} \), which corresponds to a rotational velocity of 0.04 km s\(^{-1}\) at a radius of 370 AU.

3. The mass-loss rate (\( \sim 2.3 \times 10^{-7} \, M_\odot \, \text{yr}^{-1} \)) and the momentum flux (\( \sim 3.7 \times 10^{-5} \, M_\odot \, \text{yr}^{-1} \, \text{km s}^{-1} \)) of the HV \( \text{C}^{18}\text{O} \) jets in B335 are one order of magnitude lower than those in other protostellar sources such as HH 212 and HH 211. There is no thermal SiO emission found in B335, while intense SiO and H\(_2\) emissions were found in HH 212 and HH 211. These results imply that the jet phenomena in B335 are less active. We suggest that the lower bolometric luminosity and, hence, the lower mass accretion in B335 are related to a weaker jet activity than that in the more luminous protostellar sources. The jet activities in B335 are most likely episodic because of the presence of the chain of the discrete HH objects, and it is considered to be linked to the episodic accretion. The short dynamical timescale of the HV jets (\( \sim 45 \) years) may reflect a recent increase of the mass accretion onto the central protostar.

4. The flattened infalling envelope traced by the C\textsuperscript{18}O emission shows no signature of rotation down to a radius of \( \sim 370 \) AU. As compared to the previous single-dish studies of the envelope around B335, we found that the specific angular momentum of the envelope rotation decreases from a radius of 20,000 to 300 AU. The upper limit of the specific angular momentum (\( \sim 7 \times 10^{-5} \, \text{km s}^{-1} \, \text{pc} \)) in the region within a radius of 370 AU is one order of magnitude smaller than the angular momentum around other protostellar sources, and the estimated size of the centrifugally supported disk (\( \sim 6 \) AU) around B335 is almost two orders of magnitude smaller than that around young stellar objects in Taurus. Other more evolved sources tend to show higher angular momenta in the inner region, and a larger size for the centrifugally supported disk. We presume that the low specific angular momentum and the small inferred Keplerian disk around B335 could be due to its young age in the course of the inside-out collapse of the core with the increasing specific angular momentum as a function of the radius or the more efficient magnetic braking.

We are grateful to C.-F. Lee, N. Hirano, and Z.-Y. Li for fruitful discussions. We also acknowledge J. Karr for checking and improving our use of English in our manuscript. We thank all the SMA staff supporting this work. The research of S.T. and N.O. is supported by NSC 97-2112-M-001-003-MY2 and NSC97-2112-M-001-019-MY2, respectively.
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