THE ROTATING OUTFLOW, ENVELOPE, AND DISK OF THE CLASS-0/I PROTOSTAR [BHB2007]#11 IN THE PIPE NEBULA

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ABSTRACT

We present the results of observations toward a low-mass Class-0/I protostar [BHB2007]#11 (B59#11) in the nearby ($d = 130$ pc) star-forming region Barnard 59 (B59), in the Pipe Nebula. We utilize the Atacama Submillimeter Telescope Experiment (ASTE) 10 m telescope ($\sim 22''$ resolution), focusing on the CO(3–2), HCO+, H13CO+(4–3), and $1.1$ mm dust-continuum emission transitions. We also show Submillimeter Array (SMA) data with $\sim 5''$ resolution in $^{12}$CO, $^{13}$CO, C$^{18}$O(2–1), and $1.3$ mm dust-continuum emission. From ASTE CO(3–2) observations, we found that B59#11 is blowing a collimated outflow whose axis lies almost on the plane of the sky. The outflow traces well a cavity-like structure seen in the $1.1$ mm dust-continuum emission. The results of SMA $^{13}$CO and C$^{18}$O(2–1) observations have revealed that a compact and elongated structure of dense gas is associated with B59#11; the structure is oriented perpendicular to the outflow axis. There is a compact dust condensation with a size of $350 \times 180$ AU seen in the SMA $1.3$ mm continuum map, and the direction of its major axis is almost the same as that of the dense gas elongation. The distributions of $^{13}$CO and C$^{18}$O emission also show velocity gradients along their major axes, which are thought to arise from the envelope/disk rotation. From detailed analysis of the SMA data, we infer that B59#11 is surrounded by a Keplerian disk with a radius of less than $350$ AU. In addition, the SMA CO(2–1) image shows a velocity gradient in the outflow in the same direction as that of the dense gas rotation. We suggest that this velocity gradient indicates rotation in the outflow.

Key words: ISM: clouds – ISM: individual objects ([BHB2007]#11) – ISM: molecules – radio continuum: ISM – stars: formation

Online-only material: color figures

1. INTRODUCTION

Stars are formed from the gravitational collapse of a molecular cloud core. During the collapse, the system undergoes an increase in density of 20 orders of magnitude. In the course of the gravitational collapse, the core is thought to spin up and eventually a Keplerian disk is formed around the protostar. This core grows in size during the main accretion phases.

Previous interferometric observations in molecular lines have found evidence of Keplerian disks around protostars in their main accretion phases (e.g., Brinch et al. 2007; Lommen et al. 2008; Jørgensen et al. 2009). These protostars, however, have somewhat high bolometric temperatures ($T_{\text{bol}} = 238$ K, $391$ K, $351$ K, and $310$ K for L1489-IRS, Elias 29, IRS 63, and IRS 43, respectively), indicating that these are more evolved protostars than the Class-0 phase. The initial conditions of disks have not been revealed yet. Takakuwa et al. (2012) and Lee (2010) also found Keplerian disks around Class-I protobinary systems in earlier evolutionary phases (L1551NE: $T_{\text{bol}} = 91$ K, HH111: $T_{\text{bol}} = 78$ K). There are, however, few samples of Keplerian disks observationally identified around early-phase protostars.

Barnard 59 (B59) is an irregularly shaped dark cloud sitting at the end of the Pipe Nebula. Here, we adopt a distance to B59 of $130 \pm 13$ pc (Lombardi et al. 2006), which has been most commonly used in previous studies of the Pipe Nebula. Although Alves & Franco (2007) proposed a distance of $145 \pm 16$ pc, our adopted distance is consistent within the uncertainties of their analyses. It should be noted that masses estimated in this paper have uncertainties of $\sim 20\%$ arising from a distance uncertainty of $\sim 10\%$. Onishi et al. (1999) carried out mapping observations toward the Pipe Nebula in the CO(1–0) and C$^{18}$O(1–0) lines, and detected 14 C$^{18}$O dense cores. A CO(1–0) outflow was detected only for B59, suggesting that B59 is the only active star-forming region in the Pipe Nebula (Onishi et al. 1999). Spitzer observations have revealed 20 low-mass young stellar objects (YSOs) and suggest that the star formation efficiency of the cluster is $\sim 20\%$ (Brooke et al. 2007). More detailed photometry in MIPS bands has revealed that there are 15 low-mass YSOs in a $0.3 \times 0.3$ pc area (Forbrich et al. 2009). The median stellar age of B59 has been estimated to be $2.6^{+1.1}_{-0.4}$ Myr (Covey et al. 2010). [BHB2007]#11 (hereafter B59#11) is a deeply embedded low-mass protostar in the B59 region and is classified as a Class-0/I object. These types of objects are in the transition phase from Class-0 to I with a bolometric temperature of $70$ K (Brooke et al. 2007) and are considered to be younger than the B59 median stellar age of $\sim 2.6$ Myr. B59#11 is the strongest $70 \mu$m emission source in the B59 region and has a bolometric luminosity of $2.2 \pm 0.3 L_{\odot}$ (Brooke et al. 2007) detected extended IRAC $3.6 \mu$m and $4.5 \mu$m emission to the northeast of B59#11. These structures imply that a molecular outflow ejected from B59#11 creates a cavity. Riaz et al. (2009) analyzed these extended nebulosities and suggested that the inclination angle of the outflow ejected from B59#11 is $53^{\circ} - 59^{\circ}$. Duarte-Cabral et al. (2012), however, found that the outflow...
associated with B59#11 is ejected almost in the plane of the sky from observations of molecular outflows in the CO(3–2) line. Riaz et al. (2009) also pointed out that B59#11 is building up a weakly bounded binary system with 2M17112255-27243448 (hereafter B59#11SW; the apparent separation is ~1300 AU).

We present the results of the Atacama Submillimeter Telescope Experiment (ASTE) 10 m telescope observations in CO(3–2), HCO+, H13CO+(4–3), and 1.1 mm dust-continuum emissions, and Submillimeter Array (SMA) observations in 12CO, 13CO, C18O(2–1), and 1.3 mm dust-continuum emission toward the low-mass Class-0/I protostar B59#11. This object is thought to be a good target for investigating disk formation in early protostellar evolution. First, we present the details of our ASTE observations and SMA data reductions in Section 2. In Section 3, we show the results of the ASTE and SMA observations and derive the physical properties of the outflow and the dense gas associated with B59#11. In Section 4, we discuss the possibility that B59#11 has a rotationally supported disk and a rotating outflow. Finally, we summarize our main conclusions in Section 5.

2. OBSERVATIONS

2.1. AzTEC/ASTE Observations

We carried out 1.1 mm dust-continuum observations toward the B59 region with the AzTEC camera (Wilson et al. 2008) mounted on the ASTE 10 m telescope (Ezawa et al. 2004; Kohno et al. 2004) located at Pampa la Bola (altitude = 4800 m), Chile. The observations were performed over the period 2008 October 17–31. The weather conditions during the period were good or moderate, and the typical atmospheric opacity at 225 GHz was in the range of 0.04–0.2. The AzTEC camera is a 144-element bolometric camera and has an angular resolution of 28″ in FWHM (Wilson et al. 2008). The 1.1 mm continuum observations of B59 were performed as part of a survey of nearby star-forming regions (R. Kawabe et al. 2013, in preparation). The observations were performed in the raster scan mode toward the 35′ × 35′ area centered on (α2000, δ2000) = (17h11m58.57s, −27d24′27″36s). Each field was observed several times with azimuth and elevation scans. The separation among scans was adopted to be 117″, which is a quarter of the AzTEC field of view (FoV; ~7.8″). The scanning speed of the telescope was 250″ s⁻¹. In total, 28 individual maps of the entire field, each with an integration time of 9.4 minutes, were obtained and the interpolated pointing offset was applied to each target map. The pointing accuracy of the AzTEC map is estimated to be better than 2″. The flux scale was calibrated by observing the planet Uranus twice per night, and we measured the flux conversion factor (FCF) from the optical loading value (in watts) to the source flux (in Jy beam⁻¹) for each detector element. A principal component analysis (PCA; Scott et al. 2008) cleaning method was applied to remove atmospheric noise. Details of the flux calibration are described in Wilson et al. (2008) and Scott et al. (2008). Since the PCA method is not sensitive to extended sources, we applied an iterative mapping method (FRUIT; Liu et al. 2010; Shimajiri et al. 2011) to recover the extended components. The noise level is ~6 mJy beam⁻¹ in the central region and ~7 mJy beam⁻¹ in the outer edge. The effective beam size of ~36″ is estimated from Gaussian fits to the point source in the map. We also use the CLEANed image of the PCA map to estimate parameters for point sources, in order to avoid contamination due to the extended emission seen in the FRUIT map. The PCA cleaning method produced a negative hole around the point-like source, due to the point-spread function (PSF; see Tsukagoshi et al. 2011). A CLEANed map was made by subtracting the measured PSF from emission via the CLEAN algorithm and by convolving the Gaussian beam with the FWHM of 35″ to CLEAN components. Details are described in R. Kawabe et al. (2013, in preparation).

2.2. ASTE 12CO(3–2), HCO+(4–3), and H13CO+(4–3) Line Observations

We observed the 12CO (J = 3–2; 345.796 GHz), HCO+ (J = 4–3; 356.734 GHz), and H13CO+ (J = 4–3; 346.998 GHz) transitions toward the B59 region between 2011 May and 2012 January. The half-power beam width of the ASTE telescope is ~22″ at the CO(3–2) frequency. The typical system noise temperature with the 345 GHz SIS heterodyne receiver was 300–600 K during our observations. The temperature scale was determined by the chopper wheel method (Kutner & Ulrich 1981), which provides us with an antenna temperature corrected for atmospheric attenuation. As a back end, we used four sets of a 1024 channel auto-correlator, which provided a frequency resolution of 125 kHz corresponding to ~0.1 km s⁻¹ at the HCO+(4–3) and H13CO+(4–3) frequencies. The on-the-fly (OTF) mapping technique was used to construct a map covering an area of 15′ × 11′ (corresponding to 0.6 × 0.4 pc) in CO(3–2) emission. In addition, the position-switching mode was used to construct two smaller maps of H12CO+ and HCO+ emission, the first with an area of 60′ × 60′ (corresponding to 0.04 × 0.04 pc) and the second with an area of 80′ × 80′ (corresponding to 0.05 × 0.05 pc). In both maps, a grid separation of 20″ was used. The telescope pointing was checked every 2 hr by five-point scans of the point-like 12CO (J = 3–2) emission from Waql (α2000 = 19h15m23.35s, δ2000 = +00°02′50″3″), and IRAS 16594−4656 (α2000 = 17h03m30″03s, δ2000 = −47°00′27″68″). The pointing errors were measured to be from 1″ to 2″ during the observations. The main beam efficiency is 50%. We subtracted linear baselines from the OTF spectra, then we convoluted the maps with a spherical function and resampled them onto a 7.5″ grid. Since the telescope beam size is 22″, the effective FWHM resolution in the restored images is 27″. The scanning effect was minimized by combining scans along the right ascension and declination directions, using the PLAIT algorithm developed by Emerson & Graeve (1988). The typical rms noise level in the final image is 1.5 K in T_A, at a velocity resolution of 0.1 km s⁻¹. Details of the ASTE observations are summarized in Table 1.

2.3. SMA Data Reduction

We also processed archival data from SMA observations of B59#11 and constructed both continuum and spectral line images. 1.3 mm continuum emission was observed with SMA in the compact configuration (seven antennas). The minimum and maximum baselines are 7 kλ and 50 kλ, respectively. 12CO (J = 2–1; 230.538 GHz), 13CO (J = 2–1; 220.399 GHz), and C18O (J = 2–1; 219.560 GHz) emission transitions were observed simultaneously with the 1.3 mm continuum emission. The raw data were calibrated using the MIR package for IDL that was developed for reduction of SMA data based on the Owens Valley Radio Observatory MMA package (Scoville et al. 2003).
Table 1
Parameters of the ASTE Observations

| Telescope/Receiver | ASTE/AzTEC | ASTE/CATS345 | ASTE/CATS345 | ASTE/CATS345 |
|--------------------|------------|--------------|--------------|--------------|
| Line/frequency/wavelength | 1.1 mm | $^{12}$CO ($J = 3–2; 345.796$ GHz) | HCO$^+$ ($J = 4–3; 356.734$ GHz) | $^{13}$CO$^+$ ($J = 4–3; 346.998$ GHz) |
| Observation date | 2008 Oct 17–31 | 2011 May 30–Jun 1 | 2011 May 30–Jun 1, 2012 Jan 23 | 2012 Jan 23 |
| Observation mode | Raster | OTF/position switch | Position switch | Position switch |
| Mapping size | $35' 	imes 35'$ | $15' 	imes 11'$ and $80' 	imes 80'$ | $80' 	imes 80'$ and $60' 	imes 60'$ | $60' 	imes 60'$ |
| Effective beam size | $36''$ | $27''$ (OTF)/$22''$ (position switch) | $22''$ | $22''$ |
| Velocity resolution | ... | $0.10$ km s$^{-1}$ | $0.11$ km s$^{-1}$ | $0.10$ km s$^{-1}$ |
| Typical rms | $7$ mJy beam$^{-1}$ | $0.36$ K $T_A^*$ | $0.1$ K $T_A^*$ and $0.03$ K $T_A^*$ | $0.03$ K $T_A^*$ |

Table 2
Parameters of the SMA Data Reduction

| Line/Wavelength | 1.3 mm | $^{12}$CO ($J = 2–1$) | $^{12}$CO ($J = 2–1$) | $^{13}$O ($J = 2–1$) |
|----------------|--------|---------------------|---------------------|---------------------|
| Frequency (GHz) | 220.5 and 230.5 | 230.538 | 220.399 | 219.560 |
| Observation date | 2008 Mar 25 | | | |
| Array configuration | Compact (7 ant, minimum baseline = 7 kλ, maximum baseline = 50 kλ) | | | |
| Bandwidth/channel separation | 2.0 + 2.0 GHz | 1.1 km s$^{-1}$ | 1.1 km s$^{-1}$ | 1.1 km s$^{-1}$ |
| Pointing center | $(\alpha_{2000.0}, \delta_{2000.0}) = (17^{h}11^{m}23^{s}18.1, -27^\circ24'31.5'')$ | | | |
| On source time | 14 minutes | | | |
| System temperature | 80–130 K in SSB | | | |
| Bandpass calibrators | 3C454.3 | | | |
| Complex gain calibrator | NRAO530, J1924–292 | | | |
| Absolute flux calibrators | Callisto | | | |
| Beam size | $5'0' 	imes 2'8' (31)$ | $4'8' 	imes 2'8' (31)$ | $4'8' 	imes 2'9' (30)$ | $5'2' 	imes 2'9' (32)$ |
| Map rms | $12$ mJy beam$^{-1}$ | $200$ mJy beam$^{-1}$ | $200$ mJy beam$^{-1}$ | $200$ mJy beam$^{-1}$ |

In the reduction, visibilities with clearly deviating phases and/or amplitudes were flagged. Observations of the calibrators NRAO530 and J1924–292 were interleaved with the target for complex gain calibration. The passband response was calibrated using the strong source 3C454.3. The absolute flux scale was determined by a bootstrap method with Callisto and should be accurate at the 10% level based on comparisons of quasar fluxes with the SMA calibration database. The phase reference center toward the target is $(\alpha_{2000.0}, \delta_{2000.0}) = (17^{h}11^{m}23^{s}18.1, -27^\circ24'31.5'')$. After the calibrations, final CLEANed images were made using MIRIAD (Sault et al. 1995) with natural UV weighting. The resulting synthesized beam size was $5'0' 	imes 2'8'$ (corresponding to $650 \times 360$ AU) with a position angle (P.A.) of $31^\circ$ for the dust-continuum map. The rms noise levels were $12$ mJy beam$^{-1}$ for the dust-continuum map and $200$ mJy beam$^{-1}$ for the $^{12}$CO, $^{13}$CO, and CO(2–1) images. The final images were uncorrected for the primary beam attenuation. Details of the observations are summarized in Table 2.

3. RESULTS

3.1. Large-scale Structure of B59

3.1.1. AzTEC/ASTE 1.1 mm Dust-continuum Emission

Figure 1 shows the AzTEC/ASTE 1.1 mm FRUIT image obtained toward the north end of the Pipe Nebula. The image shows two dusty clumps which correspond to Core 1 (i.e., B59) and Core 2 detected in a previous low spatial resolution $^{13}$CO(1–0) map (Onishi et al. 1999). The clump associated with Core 2 has a filamentary structure $\sim0.6$ pc long. In addition, other filamentary structures were also detected in our map. These overall structures are in good agreement with the $A_V$ map produced from infrared observations and the 1.2 mm dust-continuum map (Román-Zúñiga et al. 2009, 2012). The B59 clump consists of several dust condensations visible in 1.1 mm dust-continuum emission. The peak positions of four condensations coincide with the positions of YSOs [BHB2007]$#1$, #9, #10, and #11 identified in infrared surveys (Brooke et al. 2007). Details of these condensations are summarized in Table 3. The dust-continuum emission associated with B59#11 is the strongest in the B59 region, and has a peak intensity of 1.9 Jy beam$^{-1}$. To the northeast of B59#11, a cavity-like structure $\sim0.06$ pc long was found to be elongated along the southwest–northeast direction. This feature coincides with the one found in the $A_V$ map (Román-Zúñiga et al. 2009).

The mass of B59 (Core 1), $M_{\text{dust}}$, was derived to be $24$ M$\odot$ from the 1.1 mm total flux obtained from the FRUIT image, $F_\nu$, using

$$M_{\text{dust}} = \frac{\nu^2 d^2}{\kappa_\nu B_\nu(T_d)},$$

(1)

where we assume that all the 1.1 mm dust-continuum emission arises from the dust and is optically thin. Here, we adopt the mass opacity coefficient, $\kappa_\nu = 0.1(250 \mu m/\lambda)^0 \text{cm}^2 \text{g}^{-1}$ (Hildebrand 1983) and $\beta = 2$, which is a typical value in the interstellar medium (Knacke & Thomson 1973). For the dust temperature, we adopted $T_d = 10$ K, which is derived from observations in NH$_3$ lines (Rathborne et al. 2008). The estimated mass is in good agreement with the value of $22.4$ M$\odot$ derived by Román-Zúñiga et al. (2009) from the $A_V$ map. The mass of the dusty filament (corresponding to Core 2) is estimated to be $4.3$ M$\odot$ from the FRUIT map.

The mass of the dust condensation associated with B59#11 is also estimated using Equation (1). Here, we used the CLEANed PCA map in order to avoid contamination due to the extended emission seen in B59, since the CLEANed PCA map is less sensitive to extended emission than the FRUIT map (see Scott et al. 2008 for PCA and R. Kawabe et al. 2013, in preparation for CLEANed PCA). The peak flux density of the dust condensation associated with B59#11 is 1.3 Jy beam$^{-1}$, based on the CLEANed PCA map with an effective beam size of $36''$. For optically thin emission, the spectral slope between two
Figure 1. AzTEC/ASTE 1.1 mm dust-continuum map. The white box shows the area of Figure 3 and the yellow box shows the observing area of ASTE CO(3–2) emission (Figure 4). Contours start at the 3σ noise level with an interval of 6σ (1σ = 7 mJy beam\(^{-1}\)). The B59 mass is derived from emission within the pink contour (≥10σ; Section 3.1.1). The crosses, circles, and boxes show the positions of Class-I, flat, and Class-II YSOs, respectively (Forbrich et al. 2009). The white circles in panel (a) show the locations and the extents of Core 1 and Core 2 identified by Onishi et al. (1999). (A color version of this figure is available in the online journal.)

frequencies, \( \alpha = (\log(F_{\nu1}/F_{\nu0})/\log(\nu_1/\nu_0)) \), will be related to the slope, \( \beta \), of the dust opacity law, \( \kappa \propto \nu^{\beta} \), as \( \alpha \approx \beta + 2 \) in the Rayleigh–Jeans limit (Beckwith & Sargent 1991). Using the flux estimated from the SHARC-II 350 \( \mu \)m map for a 40\( '' \) aperture of \( F_{350\mu m} = 45.2 \) Jy (Wu et al. 2007) and \( F_{1.1\,mm} \) from the AzTEC/ASTE observations, the spectral slope, \( \alpha \), is estimated to be 3.0\(^{+0.1}_{-0.2} \) and \( \beta \) is estimated to be \( \sim 1 \). The dust temperature is estimated to be \( \sim 31 \) K by a graybody fit with MIPS 70 \( \mu \)m (Brooke et al. 2007), SHARC-II 350 \( \mu \)m (Wu et al. 2007), and AzTEC 1.1 mm emission using \( \beta = 1 \) (Figure 2). The 70 \( \mu \)m flux possibly contains emission from the central star, and this temperature gives an upper limit of the dust temperature. Using these values, the mass of the dust condensation associated with B59\#11 is estimated to be \( 0.09 \pm 5.3 \times 10^{-4} \) \( M_\odot \). The FWHM of the 1.1 mm dust condensation associated with B59\#11 is \( 37'' \times 33'' \) (P.A. = \( -47^\circ \)); the deconvolved size cannot be estimated since the dust condensation is not resolved. Román-Zúñiga et al. (2012) estimated that the deconvolved size of the dust condensation associated with B59\#11 is \( 18'' \times 17'' \) from 1.2 mm dust-continuum observations with a beam size of 11\( '' \). Using this value, the mean gas density, \( n \), is estimated by assuming a spherically symmetric shape and using a geometric mean radius, as follows:

\[
n = \frac{M_{\text{dust}}}{(4/3)\pi [(D_{\text{maj}}/2)(D_{\text{min}}/2)^3] \mu_g m_{\text{H}_2}}.
\]

Here, \( D_{\text{maj}} \) and \( D_{\text{min}} \) are the source sizes along the major and minor axes, respectively, \( \mu_g \) is the mean atomic weight per hydrogen atom set to 1.36. The mean gas density is estimated to be \( n = 1.9 \times 10^6 \) cm\(^{-3} \).

3.1.2. ASTE \( ^{12}\text{CO}(3–2) \) Emission

Here, we show our CO(3–2) data with ASTE, especially focusing on high velocity components (see Figures 3 and 4). Our ASTE CO(3–2) data show that the CO(3–2) line profiles around...
We identify a molecular outflow from B59#11 using the ASTE observations. Here, we estimate the molecular outflow ejected from B59#11 (Figure 5). Here, infrared emission are from Brooke et al. (2007), and the flux densities of the dust-continuum sources are strongly suggested to be unresolved, and we cannot obtain the deconvolved sizes.

$\sum g \text{ Estimated using the deconvolved size of } 18'$

$\sum f \text{ Estimated on the assumption that}$

$\sum d \text{ These dust-continuum sources are strongly suggested to be unresolved, and we cannot obtain the deconvolved sizes.}$

$\sum c \text{ Separations between the peak positions of the AzTEC}$

$\sum b \text{ Estimated on the assumption that}$

$\sum a \text{ From Brooke et al. (2007).}$

The CO(3–2) profiles have high-velocity wings that are roughly aligned in the same direction as the extended nebulosity seen in the IRAC 3.6 $\mu$m and 4.5 $\mu$m images (Brooke et al. 2007). This alignment indicates that these high-velocity components are the outflow wings. The cavity-like structure to the northeast of B59#11 seen in the AzTEC/ASTE 1.1 mm dust-continuum image coincides with the outflow; especially the northeast of B59#11 with lengths of 0.2 pc and 0.1 pc, respectively.

2. High-velocity emission is mostly centered on B59#11.

The CO(3–2) profiles have high-velocity wings that probably originate from the outflows from the YSOs, [BHB2007]#1, #9, and #10. The outflow lobes of these YSOs can be seen in Figure 3.

1. Both blueshifted and redshifted emission is seen to the northeast of B59#11 with lengths of $\sim$0.2 pc and $\sim$0.1 pc, respectively.

B59#11 have high-velocity wings that probably originate from the molecular outflow ejected from B59#11 (Figure 5). Here, we identify a molecular outflow from B59#11 using the ASTE CO(3–2) data, and derive the physical properties of the outflow (Table 4).

From inspection of the CO(3–2) velocity channel maps (Figure 3) and the profile map (Figure 5), we consider that the cloud component has a velocity range of $V_{\text{LSR}} = 1.5$–5.5 $\text{km s}^{-1}$. The components with velocities smaller than $V_{\text{LSR}} = 1.5$ $\text{km s}^{-1}$ and larger than 5.5 $\text{km s}^{-1}$ are considered to correspond to the blueshifted and redshifted molecular outflow components, respectively, as shown in Figure 4. The main characteristics of the CO(3–2) data are summarized as follows.

1. Both blueshifted and redshifted emission is seen to the northeast of B59#11 with lengths of $\sim$0.2 pc and $\sim$0.1 pc, respectively.

2. High-velocity emission is mostly centered on B59#11.

3. The CO(3–2) profiles have high-velocity wings that probably originate from the outflows from the YSOs, [BHB2007]#1, #9, and #10. The outflow lobes of these YSOs can be seen in Figure 3.
that the outflow associated with B59#11 is nearly along the plane of the sky and dominates the high-velocity emission in the B59 region. These overall features are in good agreement with the CO(3–2) maps in Duarte-Cabral et al. (2012). Figure 5(b) shows a profile map of the 80′ × 80′ area around B59#11 with a grid spacing of 20′. A strongly redshifted wing (and weaker blueshifted emission) exist to the southwest of B59#11, while both blueshifted and redshifted emission is seen to the northeast.

We derived physical properties of the outflow using an excitation temperature of 25 K and an outflow inclination angle of 75°, following Duarte-Cabral et al. (2012). We assumed the local thermal equilibrium (LTE) condition and used the following equation:

\[ M_j = \mu_m m_{H2} X_{CO}^{-1} \sum_i d^2 N_{CO,i,j} \]

\[ = 4.65 \times 10^{-7} \left( \frac{X_{CO}}{1.0 \times 10^{-4}} \right)^{-1} \left( \frac{d}{130 \text{ pc}} \right)^2 \left( \frac{\theta}{22'} \right)^2 \left( \frac{\eta}{0.5} \right)^{-1} \]

\[ \times \sum_i \left( \frac{T_{A,i,j}}{\text{K km s}^{-1}} \right) \left( \frac{T_{ex}}{25 \text{ K}} \right) \exp \left[ \frac{33.2}{T_{ex}} \right] M_\odot. \] (3)

The mass, momentum, and kinetic energy of the outflow are summarized in Table 4.

3.2. The Dense Gas Distribution in B59#11

3.2.1. ASTE HCO+ and H13CO+(4–3) Observations

Here, we present the dense gas distribution associated with B59#11. Figure 6 shows a 5 × 5 points profile map in ASTE HCO+(4–3) emission (black lines) taken toward B59#11 with a grid spacing of 20′, together with a 3 × 3 points profile map in H13CO+(4–3) emission (red lines) with the same grid spacing. The HCO+(4–3) emission extends over the 80′ × 80′ area. The strongest emission exists to the southwest of B59#11, (−40, −20), and has a peak temperature of ∼2.5 ± 0.12 K (\(T_A^\ast\)). The dotted line in Figure 7(b) shows the residual spectrum after subtracting an average of the surrounding four spectra from that at the center. A high-velocity component (\(V_{LSR} = −1.5–2.5 \text{ km s}^{-1}\)) exists in both the central and residual spectra. After comparing both spectra, we found that the high-velocity component is mostly spatially unresolved with the ASTE 22′ beam (corresponding to ∼3000 AU). The velocity width of the high-velocity component in HCO+ emission is almost the same as that of the dense gas rotation, \(V_{LSR} = −0.5–8.2 \text{ km s}^{-1}\) in SMA 13CO emission (\(V_{LSR} = 0.0–7.7 \text{ km s}^{-1}\); see Section 3.2.2); this finding implies that the high-velocity component corresponds to the rotating dense gas.

A velocity shift of 0.42 km s\(^{-1}\) is detected along the direction from the northwest (20′, −20′) to the southeast (−20′, 20′) of B59#11 in the HCO+ line (Figure 7). This direction coincides with that of the velocity shift associated with dense gas rotation as inferred from the SMA 13CO and C18O emission measurements (Section 3.2.2). This means that the velocity shift in...
HCO$^+$ emission possibly arises from the large-scale envelope rotation. The specific angular momentum of the outer envelope is estimated to be $3.7 \times 10^{-3}$ km s$^{-1}$ pc if the shift is due to the rotation.

The H$^{13}$CO$^+$(4–3) intensity is strongest at the center ($T_A^* \sim 0.11$ K) and no clear signature of self-absorption is found. The peak velocity and the FWHM velocity width of the central spectrum are found to be 3.6 km s$^{-1}$ and as wide as 1.7 km s$^{-1}$. The peak velocity of 3.6 km s$^{-1}$ is adopted as the systemic velocity of B59#11 in this paper.

The H$^{13}$CO$^+$(4–3) spectra are very narrow at other positions; e.g., positions at (0$''$, 20$''$) and (20$''$, −20$''$).

From the comparison of the HCO$^+$ and H$^{13}$CO$^+$ line profiles, the emission in H$^{13}$CO$^+$ corresponds to the dips in velocity in HCO$^+$; a dip is located at 3–4 km s$^{-1}$ and emission is located at 2–5 km s$^{-1}$ at the center. It indicates that the dips are formed by self-absorption. On the other hand, the HCO$^+$ intensities in the blueshifted parts are stronger than the redshifted parts to the southwest of B59#11. For example, examine positions (−20$''$, 0$''$) and (−20$''$, −20$''$) in Figure 6. These “blue-skewed” profiles are usually considered to indicate dynamical infall (e.g., Zhou et al. 1993). It is noted that a red-skewed profile is obtained at the central part of B59#11, and a simple infall model cannot account for the overall observational results.

Masses of the high-velocity components in HCO$^+$ emission are estimated using the following equation under the assumption of LTE conditions:

$$M_{\text{HCO}^+} = \mu_p m_H X_{\text{HCO}^+}^{-1} \Omega d^2 \int N_{\text{HCO}^+} dV$$

$$= 1.03 \times 10^{-2} \left( \frac{X_{\text{HCO}^+}}{1.0 \times 10^{-16}} \right)^{-1} \left( \frac{d}{130 \text{ pc}} \right)^2$$

$$\times \left( \frac{\theta}{22''} \right)^2 \left( \frac{n}{0.5} \right)^{-1} \int \left( \frac{T_A^*}{K \text{ km s}^{-1}} \right) dV$$

$$\times \left( \frac{T_{\text{ex}}}{30 \text{ K}} \right) \exp \left[ \frac{42.8}{T_{\text{ex}}} \right] M_\odot, \quad (4)$$

Figure 5. (a) CO(3–2) map (the same as Figure 4) and (b) CO(3–2) profile map taken toward B59#11. The green crosses in panel (a) show the positions where the profiles in panel (b) were obtained, and the yellow circle shows the SMA FoV. The grid spacing of panel (b) is 20$''$. The dotted vertical lines are the systemic velocity of 3.6 km s$^{-1}$ obtained from ASTE H$^{13}$CO$^+$(4–3) observations (Figure 6). The (0$''$, 0$''$) position is the peak position of the AzTEC/ASTE 1.1 mm dust-continuum condensation associated with B59#11, (α$_{2000.0}$, δ$_{2000.0}$) = (17$^h$11$^m$23$^s$, −27$^\circ$24$'$38$''$2).

(A color version of this figure is available in the online journal.)
Figure 6. ASTE HCO+(4–3) (black lines) and H13CO+(4–3) (red lines) profile maps. The dotted vertical lines are the systemic velocity. The (0′′,0′′) position and grid spacing are the same as those of Figure 5(b).

(A color version of this figure is available in the online journal.)

Figure 7. Profiles of (a) H13CO+(4–3) and (b) HCO+(4–3) lines at the (0′′,0′′) position in Figure 6. The dotted line in panel (b) shows the residual spectrum after subtracting an average of the surrounding four pixels. The dotted vertical lines are the systemic velocity and the solid vertical lines in panel (b) indicate the velocity range where the masses of the high-velocity components were obtained (Table 5). (c) Line profiles of HCO+(4–3) at the (−20′′,20′′) and (20′′,−20′′) positions.

where we assume that HCO+ emission is optically thin in the high-velocity ranges. We used $X[\text{HCO}^+] = 1.0 \times 10^{-10}$ (Rawlings et al. 2004) and $T_{\text{ex}} = 30$ K, which we adopt for the envelope/disk in this paper (Section 3.1.1) since its high-velocity component is considered to trace the rotating dense gas. The masses of the blueshifted ($V_{\text{LSR}} = -1.5$–$2$ km s$^{-1}$) and redshifted ($V_{\text{LSR}} = 5$–$8$ km s$^{-1}$) components are estimated to be $1.2 \times 10^{-2}$ and $1.8 \times 10^{-2} M_\odot$, respectively. The total mass of the high-velocity components, 0.03 $M_\odot$, is comparable to the masses obtained from the SMA 13CO and C18O data. This indicates that the high-velocity components trace the dense gas rotation in terms of the mass comparison as well as in the comparison of the velocity width described above.

The mass of the dense region traced by H13CO+(4–3) is estimated based on the assumption of LTE conditions:

$$M_{\text{H13CO}^+} = \mu_s m_H X_{\text{H13CO}^+}^{-1} \Omega d^2 \int N_{\text{H13CO}^+} dv$$

$$= 7.8 \times 10^{-1} \left( \frac{X_{\text{H13CO}^+}}{1.4 \times 10^{-12}} \right)^{-1} \left( \frac{d}{130 \text{ pc}} \right)^2$$

$$\times \left( \frac{\theta}{22''} \right)^2 \left( \frac{\eta}{0.5} \right)^{-1} \int \left( \frac{T_A}{K \text{ km s}^{-1}} \right) dv$$

$$\times \left( \frac{T_{\text{ex}}}{30 \text{ K}} \right) \exp \left[ 41.6/T_{\text{ex}} \right] M_\odot. \quad (5)$$
from the total integrated dense gas on smaller scales than those probed by the ASTE
M 13C abundance ratio of $X$. We adopt
Figure 8.
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V (a)
(A color version of this figure is available in the online journal.)
dashed lines in panels (a) and (b) indicate the cuts along which the P-V diagrams in Figures 11(a) and (b) were produced.

In this section, we show the results of the SMA 13CO and C18O(2–1) observations. These transitions are expected to trace dense gas on smaller scales than those probed by the ASTE HCO$^+$ and H13CO$^+$ observations. From the total integrated intensity maps (Figures 8(c) and (d)), we see that a compact gas condensation in 13CO and C18O emission is assumed to be optically thin, and we obtained a mass of 0.59 $M_\odot$. These results are summarized in Table 5.

3.2.2. SMA 13CO(2–1) and C18O(2–1) Emission

We adopt $X[\text{H}^{13}\text{CO}] = 1.4 \times 10^{-12}$ estimated with a C to 13C abundance ratio of ~71 (Wilson & Rood 1994). H13CO$^+$ emission is assumed to be optically thin, and we obtained a mass of 0.59 $M_\odot$. These results are summarized in Table 5.

In this section, we show the results of the SMA 13CO and C18O(2–1) observations. These transitions are expected to trace dense gas on smaller scales than those probed by the ASTE HCO$^+$ and H13CO$^+$ observations. From the total integrated intensity maps (Figures 8(c) and (d)), we see that a compact gas condensation in 13CO and C18O emission is clearly associated with B59#11 and elongated along the northwest–southeast direction. This direction is perpendicular to the molecular outflow axis identified with the ASTE CO(3–2) observations (Section 3.1.2). The C18O condensation is about half the size of the 13CO condensation, and its extent is measured to be 17″ × 11″ (corresponding to ~2000 × 1400 AU and an aspect ratio of ~1.5) and 30″ × 17″ (corresponding to ~4000 × 2000 AU and an aspect ratio of ~1.8), respectively.

A velocity gradient is evident in both the 13CO and the C18O maps (Figure 8) along the major axis of the dense gas condensation. The northwestern side of the condensation is blueshifted and the southeastern side is redshifted. Figures 11(a) and (b) show the position–velocity (P-V) diagrams which are cut along the major axis of the condensation. The velocity gradient appears to have a power-law profile, indicating that the velocity gradient arises from the dense gas rotation. The specific angular momentum is estimated to be $2.1 \pm 1.2 \times 10^{-3}$ km s$^{-1}$ pc using the results of 13CO(2–1), assuming an inclination angle of 75° (Duarte-Cabral et al. 2012).

The optical depth of the 13CO(2–1) emission is calculated assuming that the abundance ratio between 13CO and C18O is ~6 (Frerking et al. 1987). The following equation is employed:

$$\frac{T_R(13\text{CO})}{T_R(C^{18}\text{O})} = \frac{1 - \exp[-\tau_{13\text{CO}}]}{1 - \exp[-\tau_{13\text{CO}}/6]}.$$ (6)

where $T_R$ is the radiation temperature at a given velocity, $v$. The $^{13}$C emission is estimated to be optically thick for only two velocity channels that are close to the systemic velocity, $V_{\text{LSR}} = 3.3 – 4.4$ km s$^{-1}$. Note that our estimate of the optical depth includes a large uncertainty due to resolved-out emission. Under the assumption of LTE conditions, we also obtain the

Table 5

| Line            | Parameter            | −1.5–2 km s$^{-1}$ | 2–4 km s$^{-1}$ | 5–8 km s$^{-1}$ | Total   |
|-----------------|----------------------|-------------------|----------------|----------------|---------|
| HCO$^+$(4–3)    | Integrated intensity | 0.28              | 2.5            | 0.41           | 3.2     |
|                 | Mass ($M_\odot$)     | $1.2 \times 10^{-2}$ | …              | $1.8 \times 10^{-2}$ | $3.0 \times 10^{-2}$ |
| H13CO$^+$(4–3)  | Integrated intensity | …                 | 0.17           | …              | …       |
|                 | Mass ($M_\odot$)     | …                 | 0.53           | …              | 0.53    |

Note. Masses are estimated on the assumption of optically thin emission, $T_{\text{ex}} = 30$ K, $X[\text{H}^{13}\text{CO}] = 1.0 \times 10^{-10}$, and $X[\text{H}^{15}\text{CO}] = 1.4 \times 10^{-12}$.
mass of dense gas traced by $^{13}$CO(2–1) emission as follows:

$$M_{^{13}\text{CO}} = \sum_j M_j = 5.11 \times 10^{-5} \left( \frac{X_{^{13}\text{CO}}}{1.7 \times 10^{-6}} \right)^{-1} \left( \frac{d}{130 \text{pc}} \right)^2 \times \sum_i \left( \frac{S_{i,j}}{\text{Jy km s}^{-1}} \right) \left( \frac{T_{\text{ex}}}{30 \text{K}} \right) \exp \left[ \frac{15.9}{T_{\text{ex}}} \right] \frac{T_{^{13}\text{CO}}}{1 - e^{-T_{^{13}\text{CO}}}} M_\odot. \quad (7)$$

We used $T_{\text{ex}} = 30 \text{ K}$ and $X[^{13}\text{CO}] = 1.7 \times 10^{-6}$ (Frerking et al. 1987). From a total integrated flux of 30.4 Jy km s$^{-1}$, the mass is estimated to be $3.7 \times 10^{-5} M_\odot$. Under the assumption of LTE conditions and optically thin emission (Frerking et al. 1982), we compute the mass of dense gas traced by C$^{18}$O(2–1) emission as follows:

$$M_{\text{C}^{18}\text{O}} = \sum_j M_j = 3.03 \times 10^{-4} \left( \frac{X_{\text{C}^{18}\text{O}}}{3.0 \times 10^{-7}} \right)^{-1} \left( \frac{d}{130 \text{pc}} \right)^2 \times \sum_i \left( \frac{S_{i,j}}{\text{Jy km s}^{-1}} \right) \left( \frac{T_{\text{ex}}}{30 \text{K}} \right) \exp \left[ \frac{15.9}{T_{\text{ex}}} \right] M_\odot. \quad (8)$$

We adopt $T_{\text{ex}} = 30 \text{ K}$ and $X[\text{C}^{18}\text{O}] = 3.0 \times 10^{-7}$ (Frerking et al. 1987). Using a total integrated flux of 8.9 Jy km s$^{-1}$, the mass is derived to be $3.3 \times 10^{-2} M_\odot$.

3.3. SMA 1.3 mm Dust-continuum Emission

Figure 9 shows the distribution of 1.3 mm dust-continuum emission obtained from SMA observations. A compact and strong dust condensation associated with B59#11, centered at $(\alpha_{2000.0}, \delta_{2000.0}) = (17^\text{h}11^\text{m}23.08^\text{s}, -27°24′50″)$, is detected. The FWHM size of the dust condensation is measured to be $5.5 \times 8.5$ (P.A. = 29°), and its deconvolved size is estimated to be $2.7 \times 1.4$ ($\sim 350 \times 180 \text{ AU}$; P.A. = −15°). The condensation is oriented along the same direction as the elongation of the dense gas distributions in the SMA $^{13}$CO and C$^{18}$O emission observations (see Sections 3.2.2). The peak intensity and total integrated flux density are $0.49 \pm 0.012 \text{ Jy beam}^{-1}$ and 0.67 Jy, respectively. The mass and mean gas density are estimated to be $\sim 7.3 \times 10^{-2} M_\odot$ and $1.1 \times 10^6 \text{ cm}^{-3}$, using Equation (1) and the same assumptions as those used in the estimate for the AzTEC/ASTE 1.1 mm data (see Section 3.1). The separation between the position of B59#11 defined by Forbrich et al. (2009) and the SMA peak position is $\sim 0.3$, i.e., smaller than the position accuracy of the infrared images. At the position of B59#11SW, no dust condensation has been detected and the disk or envelope mass associated with B59#11SW is estimated to be lower than $4.9 \times 10^{-4} M_\odot$ ($3\sigma$ noise level) with $\beta = 2$. This suggests that B59#11SW is not embedded in the massive envelope and may be a more evolved source.

3.4. SMA $^{12}$CO(2–1) Emission—The Velocity Gradient in the Molecular Outflow

We have detected an interesting internal structure in the outflow associated with B59#11. Figure 10 shows blueshifted ($V_{\text{LSR}} = 4.9 - 1.4 \text{ km s}^{-1}$) and redshifted ($V_{\text{LSR}} = 4.6 - 12 \text{ km s}^{-1}$) components detected by SMA CO(2–1) observations. We identified three blueshifted and redshifted lobes in Figure 10; one blueshifted and one redshifted lobe are projected toward the northeastern side of B59#11, while the third redshifted lobe is projected toward the southwestern side. The lengths of the lobes are $\sim 2400 \text{ AU}$, $3100 \text{ AU}$, and $2400 \text{ AU}$, respectively. In both maps of the ASTE CO(3–2) and SMA CO(2–1) data, the blueshifted and redshifted components exist on the northeastern side of B59#11, while only a redshifted component exists on the southwestern side. This shows that the high-velocity components observed in the SMA CO map trace the molecular outflow ejected from B59#11. The mean velocity map of SMA CO emission (Figure 10(b)) shows the velocity gradient in the outflow lobe located on the northeast; the northeastern side of the outflow lobe is blueshifted and the southern side is redshifted. The direction of the velocity gradient in the outflow is the same as that of the dense gas rotation shown in Section 3.2.2.

The mass, momentum, and energy are estimated from the following equation:

$$M_{\text{CO}} = \sum_j M_j = 6.09 \times 10^{-7} \left( \frac{X_{\text{CO}}}{1.0 \times 10^{-4}} \right)^{-1} \left( \frac{d}{130 \text{pc}} \right)^2 \times \sum_i \left( \frac{S_{i,j}}{\text{Jy km s}^{-1}} \right) \left( \frac{T_{\text{ex}}}{25 \text{K}} \right) \exp \left[ 16.6/T_{\text{ex}} \right] M_\odot. \quad (9)$$

We apply the same parameters as those of Equation (3) and assume that CO(2–1) emission is optically thin. The masses for the blueshifted and redshifted outflows are derived to be $2.8 \times 10^{-4}$ and $4.4 \times 10^{-4} M_\odot$, respectively. We note that CO lines often become optically thick even toward outflow wing components, and thus the estimates of the outflow mass, momentum, and energy are probably lower limits. Moreover, it is shown that roughly 90% of the emission is resolved out in SMA data, based on a comparison with the flux density estimated from the ASTE CO(3–2) emission. The energies and momenta are also summarized in Table 4 together with the masses.

4. DISCUSSION

4.1. Kinematics and Physical Properties of the Rotating Envelope and Disk

4.1.1. Kinematical Evidence for the Formation of the Keplerian Disk

As described in Section 3.2.2, the $^{13}$CO and C$^{18}$O(2–1) emission is oriented perpendicular to the outflow direction and
Figure 10. Maps of SMA CO(2–1) emission. The blue and red contours represent blueshifted and redshifted intensities integrated between $V_{\text{LSR}} = -4.9$ to 1.4 km s$^{-1}$ and 4.6 to 12 km s$^{-1}$, respectively. The white contours superposed on the mean velocity map in (b) indicate the emission integrated over intervals from $V_{\text{LSR}} = -4.9$ to 12 km s$^{-1}$. Contours start at the 3σ noise level with intervals of (a) 1.5σ (1σ = 1.0 Jy beam$^{-1}$ km s$^{-1}$) and (b) 3σ (1σ = 1.8 Jy beam$^{-1}$ km s$^{-1}$). The symbols in each figure are the same as those in Figure 9. The dashed lines in panel (a) are cuts along which the P-V diagrams in Figures 11(c) and (d) were produced.

(A color version of this figure is available in the online journal.)

Figure 11. Position–velocity diagrams in (a) SMA $^{13}$CO(2–1), (b) C$^{18}$O(2–1), and (c, d) CO(2–1) emission, cut along lines with a P.A. of 145° centered at B59#11 (Figures 8 and 10). Contours start at (a, c, d) the 3σ and (b) 1.5σ noise level with intervals of (a) 3σ (1σ = 0.2 Jy beam$^{-1}$), (b) 1.5σ (1σ = 0.2 Jy beam$^{-1}$), and (c, d) 6σ (1σ = 0.2 Jy beam$^{-1}$), respectively. The blue dashed lines in the vertical and horizontal directions show the systemic velocity and the position of B59#11. The red thick and narrow lines show Keplerian disk models for the central masses of 1.0 $M_\odot$ and 0.5 $M_\odot$, and the green curves show the rotation conserving its angular momentum ($r \propto v^{-1}$) whose rotational velocity is 2 km s$^{-1}$ at a radius of 200 AU.

(A color version of this figure is available in the online journal.)
shows a velocity gradient along its major axis. This emission is probably tracing a rotating flattened envelope or a disk of dense gas. The specific angular momentum of this system is as large as $2.1 \times 10^{-3}$ km s$^{-1}$ pc (as described in Section 3.2.2). It is, therefore, expected that the centrifugal radius (the radius at the outer edge of the rotationally supported disk; $r_{\text{c}}^2/GM_*=a$) is also as large as 200–1000 AU for, e.g., $M_*=0.2–1 M_\odot$. Such a Keplerian disk can be identified. Here, we discuss whether the velocity gradient traces the rotation of the Keplerian disk or not in terms of the radial dependence of the rotation velocity.

Investigating the radial dependences of the rotational velocities allows us to discriminate two possible kinematics; the velocities should be proportional to $r^{-3/2}$ or $r^{-1/2}$ for rotation conserving its angular momentum and Keplerian rotation, respectively. We plotted radii as a function of velocities as traced by $^{13}$CO and C$^{18}$O emission in Figure 12. The radii are estimated by measuring the peak positions of emission and deriving the separations from the $1.3$ mm dust-continuum peak. Via $\chi^2$ minimizations, the power-law indexes, $\alpha$ (i.e., $v = r^\alpha + v_{\text{sys}}$) in $^{13}$CO and C$^{18}$O emission are estimated to be $-1.3$ and $-0.61$, respectively (details are shown in Table 6). These results suggest that the outer and lower density regions traced by $^{13}$CO are in better agreement with the presence of a rotating flattened envelope, while the inner, more dense regions traced by C$^{18}$O emission (or, at least, some parts of this region) are in better agreement with the presence of a rotationally-supported disk.

The existence of a disk traced by C$^{18}$O can be also inferred by comparing the dynamical mass and stellar mass obtained from the spectral energy distribution (SED) analysis. To derive the dynamical mass of B59#11, we fit Keplerian rotation (i.e., $v(r) = \sin i \sqrt{GM_*/r}$) to the C$^{18}$O data (Figure 12). The central stellar mass is estimated to be $0.73 M_\odot$ (fixed on Keplerian rotation) assuming an inclination angle of $75^\circ$. This is an upper limit on the central mass, since this inclination angle is determined based on a limitation of the outflow opening angle which gives a lower limit. The central stellar mass estimated from this fitting is not consistent with the $0.28 M_\odot$ obtained from the SED model fitting conducted by Riaz et al. (2009) using the radiative transfer model of Whitney et al. (2003) for $i = 53^\circ–59^\circ$. Our observations, however, reveal that the outflow associated with B59#11 is ejected mostly in the plane of the sky (Section 3.1.2).

We also run the SED model fitting program developed by Robitaille et al. (2007) assuming $i > 75^\circ$, and obtained a central stellar mass of $0.81 M_\odot$ as the best-fit result. The other physical parameters of the models are presented in Table 7. This model gives a better fit to data at shorter wavelengths, $\lambda < 70 \mu$m (where emission comes mostly from the central protostar or the central region), compared with the model of Riaz et al. (2009; Figure 2). The fit is, however, worse at the longer wavelengths, especially at $70 \mu$m, and this might be caused by the contamination of B59#11SW due to the larger observing beams ($8\arcsec–36\arcsec$). The estimated stellar mass from this SED analysis agrees well with the dynamical mass obtained from the SMA C$^{18}$O data. This agreement suggests a rotationally supported Keplerian disk traced by the C$^{18}$O emission.

### Table 6

| Parameter | Edge-on | Riaz et al. (2009) |
|-----------|---------|-------------------|
| \(R_* (R_\odot)\) | 5.6 | 3.4 |
| \(T_* (K)\) | 4000 | 3300 |
| \(M_*(M_\odot)\) | 0.81 | 0.28 |
| \(\theta_0\) | 75$^\circ$ | 53$^\circ$–59$^\circ$ |
| \(R_{\text{env}, \text{max}} (\text{AU})\) | 3000 | 4000 |
| \(R_{\text{disk}, \text{max}} (\text{AU})\) | 390 | 30 |
| \(M_{\text{disk}} (M_\odot)\) | $7.0 \times 10^{-3}$ | $2.6 \times 10^{-2}$ |

4.1.2. Evidence for Disk Formation from the 1.3 mm Image

Next, we also discuss whether the SMA 1.3 mm dust-continuum emission traces the disk/envelope system or exclusively the envelope. Here, we follow Jørgensen et al. (2009). They have pointed out that the SMA flux density (in 1.1 mm continuum emission) is only several percent that of single-dish observations (in 850 $\mu$m continuum emission) if there is no disk contribution for a protostar located at a distance of 125 pc. Here,
we convert the distance and wavelengths in our observations to
match their method. Using the SMA data with the baselines
$\geq 52 \, \text{k}\lambda$, the SMA to AzTEC flux density ratio is estimated to
be $16\% \pm 2\%$, where the flux densities were converted using
$\beta = 1$ (Section 3.1.1). This value is large enough to be compared
with $8\%$, which is the largest value of the envelope contribution
toward the various envelope models. This result suggests the
existence of the disk. We also note that the deconvolved size of
the 1.3 mm dust-continuum emission traces the disk.

The SMA emission can be separated into contributions from
the disk and the envelope, and individual masses are estimated using the following equations (Jørgensen et al. 2009):

$$S_{50\lambda} = S_{\text{disk}} + c \, S_{\text{env}},$$

$$S_{15'} = S_{\text{disk}} + S_{\text{env}}.$$  (10)

Here, $c$ is the fractional contribution of the envelope to the overall emission obtained by interferometric observations. Under the assumption of $c = 0.04$ (Jørgensen et al. 2009) and the same parameters as those used in Sections 3.1.1 and 3.3, the envelope and disk masses are estimated to be $8.2 \times 10^{-2}$ and $1.5 \times 10^{-3} \, M_\odot$, respectively.

From the above discussion, we conclude that in source B59#11, a rotationally supported disk has formed and that it is in an early evolutionary phase.

4.2. Comparison of the Physical Nature of the Keplerian Disks of B59#11 and L1551NE

Recently, a Keplerian disk was found in the protobinary system L1551NE, a young Class-I protostar with a low bolometric temperature ($T_{\text{bol}}$) of 91 K (Takakuwa et al. 2012). B59#11 also has a low bolometric temperature of 70 K, comparable to that of L1551NE. Thus, the comparison with L1551NE provides us with valuable information of disk formation in the early phases of protostellar evolution.

The dust mass of L1551NE obtained from the SMA observations is $0.016 \, M_\odot$ (Takakuwa et al. 2012). This compares well to the value obtained for B59#11 of $0.015 \, M_\odot$ (see Section 4.1.2) using the same mass opacity coefficient. The disk mass, central stellar mass, and the bolometric temperature of B59#11 are comparable with those of L1551NE, as shown in Table 8.

The disk sizes are possibly similar, too. On the other hand, the disk around B59#11 is a "protostellar" disk, while the disk around L1551NE is a "protobinary" disk.

Machida et al. (2004) have revealed that it is difficult to fragment a disk under a strong magnetic field even if the initial specific angular momentum is large. On the other hand, Román-Zúñiga et al. (2012) have suggested that a magnetic field with a strength of $\sim 0.1-0.2 \, \mu\text{G}$ is required to support the B59 clump against further fragmentation. This value seems to be larger than the strength of the magnetic field in the Taurus molecular cloud ($\sim 10-50 \, \mu\text{G}$; Levin et al. 2001; Crutcher et al. 2003). Thus, the strong magnetic field may maintain B59#11 as a single protostar.

Recent theoretical studies suggest that extended Keplerian disks may not be formed in the early phase of protostellar evolution, i.e., the Class-0 phase (e.g., Hennebelle & Fromang 2008; Dapp et al. 2012; Krasnopolsky et al. 2012). However, previous observations have shown that large Keplerian disks exist in the Class-I phase. In this paper, we have revealed that the Class-0/1 protostar B59#11 has a large Keplerian disk with a size of 350 AU. Very recently, Tobin et al. (2012) also discovered a large Keplerian disk around a Class-0 object, L1527. Hence, it remains unclear in what stage large Keplerian disks are formed. Further observational and theoretical studies are required to constrain the formation process of Keplerian disks in protostellar evolution.

4.3. A Rotating Outflow in B59#11?

We have shown that there is a velocity gradient in the same direction as the envelope rotation in the B59#11 outflow (Section 3.4). There are some interpretations of this velocity gradient, and one of these is a rotating outflow. The rotations of the outflows in CO observations were reported in the Class-I and II sources (e.g., Launhardt et al. 2009; Pech et al. 2012). The velocity structure in the northeastern lobe of the B59#11 outflow is very similar to those in outflows ejected from the Class-II YSO CB26 (Launhardt et al. 2009) and the Class-I YSO HH797 (Pech et al. 2012), two very reliable candidates for a rotating molecular outflow. The specific angular momentum of the outflow in B59#11 is estimated to be $\sim 2.3 \times 10^{-3} \, \text{km s}^{-1} \, \text{pc}$ based on a separation of the peak positions of the blueshifted and redshifted lobes of $\sim 4''$ (corresponding to 520 AU), a radial velocity of 1.8 km s$^{-1}$ (Figures 10 and 11), and an inclination angle of 75°. We note that this value is almost the same as that of CB26 and smaller than that of HH797.

Another possibility is that the outflow is ejected from a protobinary system. Such a molecular outflow is identified in, for example, IRAS 05295+1247 (Arce & Sargent 2005). This object’s outflow is composed of one blueshifted lobe and three redshifted lobes and may resemble the B59#11 outflow. An outflow from a protobinary system, however, often shows an X-shaped structure, which comprises the walls of a cone-shaped outflow cavity. Alternatively, the outflow may exhibit an S-shaped structure, which is formed by a precessing outflow (e.g., Arce & Sargent 2005; Wu et al. 2009). These structures are not confirmed in B59#11 (Figure 10).

B59#11 might constitute a binary system with the nearby (projected separation of 1000 AU) protostar, B59#11SW, as suggested by Riaz et al. (2009). Assuming that the precession of the outflow axis is driven by tidal interactions between the circumstellar disk from which the jet is launched and a
companion star on a non-coplanar orbit (e.g., Launhardt et al. 2009), the precessing timescale is expected to be the same as the binary orbital period. If the stellar masses of B59#11 and B59#11SW are both close to 1 $M_\odot$, the orbital period is estimated to be $\sim 10^5$ yr assuming that the binary separation is 4000 AU ($\sim 1000$ AU/$\cos i$, $i = 75^\circ$) from the equation $T^2 = (4\pi^2/G(M_1 + M_2))a^{3/2}$. This period would be much longer than the outflow dynamical timescale of $\sim 10^4$ yr Duarte-Cabral et al. (2012) obtained from their single-dish observations. Thus, the kinematics of the B59#11 outflow cannot be explained by the precession caused by such a very wide binary.

Is there really no evidence that B59#11 is a closed binary system? If a binary system is formed, then the tidal effects of the two protostars can transport rotational angular momentum of the common disk outward and can create a hole with a radius of $\sim 2.7r$ (where $r$ is the semi-major axis of the binary orbital; e.g., Artymowicz et al. 1991; Dutrey et al. 1994). Such signatures sometimes appear in, e.g., C$^{18}$O and/or $^{13}$CO images and P-V diagrams; continuous increasing of the rotation velocity as $r^{-1/2}$ and $r^{-1}$ is terminated at the inner edge of the disk. As discussed in Section 4.1.1, the dense inner part traced by C$^{18}$O is likely to be a rotationally supported disk. The high-velocity emission in $^{13}$CO perhaps also traces the disk as shown in Figures 11 and 12. The highest velocity of the envelope/disk rotation is about 4.6 km s$^{-1}$ in $^{13}$CO, and the rotation velocity is estimated to trace the $r = 30$ AU region if we assume that $^{13}$CO traces the Keplerian disk at the inner area. The binary separation is calculated to be smaller than 11($=30/2.7$) AU if we assume that the obtained radius is an upper limit of the inner edge of the disk and that a binary companion exists. Further observations with higher spatial resolution are needed to confirm the outflow rotation in B59#11.

5. CONCLUSIONS

We have carried out ASTE observations toward the B59 region ($d \sim 130$ pc) of the Class-0/I YSO B59#11 in the Pipe Nebula. We have imaged the region in 1.1 mm dust-continuum, CO(3–2), HCO$^+$, and H$^{13}$CO$^+$ (4–3) emission. We also processed archival data from the SMA of B59#11 in 1.3 mm dust-continuum, CO, $^{13}$CO, and C$^{18}$O(2–1) emission. The main results of these data are summarized as follows.

1. We have detected four dust condensations associated with YSOs [BHB2007]#1, #9, #10, and #11 with the AzTEC/ASTE 1.1 mm continuum observations. The dust-continuum emission associated with B59#11 is the strongest in the B59 region, and the mass of the condensation is estimated to be 0.09 $M_\odot$.

2. From ASTE CO(3–2) observations, we found that B59#11 is blowing a collimated outflow whose axis is almost on the plane of the sky. This outflow traces well a cavity-like structure seen in the AzTEC/ASTE 1.1 mm dust-continuum map. The overall structures are in good agreement with the results of Duarte-Cabral et al. (2012).

3. The SMA images of $^{13}$CO and C$^{18}$O(2–1) emission (resolution of $\sim 5''$, corresponding to $\sim 650$ AU) have revealed that a compact and elongated structure of the dense gas is associated with B59#11. This structure has a size of about 4000 $\times$ 2000 AU (with an aspect ratio of $\sim 2:1$). The dense gas shows rotation along its major axis and the specific angular momentum is estimated to be $2.1 \times 10^{-3}$ km s$^{-1}$ pc. ASTE HCO$^+$ emission also shows a velocity gradient, which is thought to arise from the large-scale envelope rotation.

4. A compact dust-continuum condensation with a mass of $7.3 \times 10^{-2}$ $M_\odot$ is identified from our SMA 1.3 mm continuum emission data. The deconvolved size of the dust condensation is estimated to be $\sim 350 \times 180$ AU; the condensation is oriented along the rotation axis of the dense gas.

5. The SMA CO(2–1) emission map shows a velocity gradient in the outflow lobe. It is thought to trace the outflow rotation and its specific angular momentum is estimated to be $2.3 \times 10^{-3}$ km s$^{-1}$ pc. This specific angular momentum is comparable to that of another rotating outflow, CB26. Further observations with higher spatial resolution, however, are needed to confirm the rotation of the B59#11 outflow.

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REFERENCES

Alves, F. O., & Franco, G. A. P. 2007, A&A, 470, 597
Arce, H. G., & Sargent, A. I. 2005, ApJ, 624, 232
Artymowicz, P., Clarke, C. J., Lubow, S. H., & Pringle, J. E. 1991, ApJL, 370, L35
Beckwith, S. V. W., & Sargent, A. I. 1991, ApJ, 381, 250
Brinch, C., Crapsi, A., Jørgensen, J. K., Hogerheijde, M. R., & Hill, T. 2007, A&A, 475, 915
Brooke, T. Y., Huard, T. L., Bourke, T. L., et al. 2007, ApJ, 655, 364
Covey, K. R., Lada, C. J., Román-Zúñiga, C., et al. 2010, ApJ, 722, 971
Crutcher, R., Heiles, C., & Troland, T. 2003, in Turbulence and Magnetic Fields in Astrophysics, ed. E. Falgarone & T. Passot (Lecture Notes in Physics, Vol. 614; Berlin: Springer), 155
Dapp, W. B., Basu, S., & Kunz, M. W. 2012, A&A, 541, A35
Duarte-Cabral, A., Chrysostomou, A., Peretto, N., et al. 2012, A&A, 543, A140
Dutrey, A., Guilloteau, S., & Simon, M. 1994, A&A, 286, 149
Emerson, D. T., & Greene, R. 1988, A&A, 190, 153
Ezawa, H., Kawabe, R., Kohno, K., & Yamamoto, S. 2004, Proc. SPIE, 5489, 763
Forbrich, J., Lada, C. J., Muench, A. A., Alves, J., & Lombardi, M. 2009, ApJ, 704, 292
Frewing, M. A., Langer, W. D., & Wilson, R. W. 1982, ApJ, 262, 590
Frewing, M. A., Langer, W. D., & Wilson, R. W. 1987, ApJ, 313, 320
Hennebelle, P., & Fromang, S. 2008, A&A, 477, 9
Hildebrand, R. H. 1983, QJRAS, 24, 267
Jørgensen, J. K., van Dishoeck, E. F., Visser, R., et al. 2009, A&A, 507, 861
Knacke, R. F., & Thomson, R. K. 1973, PASP, 85, 341
Kohno, K., Yamamoto, S., Kawabe, R., et al. 2004, in The Dense Interstellar Medium in Galaxies, ed. S. Pfalzner, C. Kramer, C. Staubmeier, & A. Heithausen (Berlin: Springer), 349
Krasnopolsky, R., Li, Z.-Y., Shang, H., & Zhao, B. 2012, ApJ, 757, 77
Ku¨tter, M. L., & Ulrich, B. L. 1981, ApJ, 250, 341
Launhardt, R., Pavlyuchenkov, Y., Gueth, F., et al. 2009, A&A, 494, 147
Lee, C.-F. 2010, ApJ, 725, 712
Levin, S. M., Langer, W. D., Velusamy, T., Kuiper, T. B. H., & Crutcher, R. M. 2001, ApJ, 555, 850
Liu, G., Calzetti, D., Yun, M. S., et al. 2010, AJ, 139, 1190
Lommen, D., Jørgensen, J. K., van Dishoeck, E. F., & Crapsi, A. 2008, A&A, 481, 141
Machida, M. N., Tomisaka, K., & Matsumoto, T. 2004, MNRAS, 348, L1
Motte, F., & Andr´e, P. 2001, A&A, 365, 440
Onishi, T., Kawamura, A., Abe, R., et al. 1999, PASJ, 51, 871
Pech, G., Zapata, L. A., Loinard, L., & Rodr´ıguez, L. F. 2012, ApJ, 751, 78
Rathborne, J. M., Lada, C. J., Muench, A. A., Alves, J. F., & Lombardi, M. 2008, ApJS, 174, 396
Rawlings, J. M. C., Redman, M. P., Keto, E., & Williams, D. A. 2004, MNRAS, 351, 1054
Riaz, B., Martín, E. L., Bouy, H., & Tata, R. 2009, ApJ, 700, 1541
Robitaille, T. P., Whitney, B. A., Indebetouw, R., & Wood, K. 2007, ApJS, 169, 328
Román-Zúñiga, C. G., Frau, P., Girart, J. M., & Alves, J. F. 2012, ApJ, 747, 149
Román-Zúñiga, C. G., Lada, C. J., & Alves, J. F. 2009, ApJ, 704, 183
Sault, R. J., Teuben, P. J., & Wright, M. C. H. 1995, in ASP Conf. Ser. 77, Astronomical Data Analysis Software and Systems IV, ed. R. A. Shaw, H. E. Payne, & J. J. E. Hayes (San Francisco, CA: ASP), 433
Scott, K. S., Austermann, J. E., Perera, T. A., et al. 2008, MNRAS, 385, 2225
Scoville, N. Z., Carlstrom, J. E., Chandler, C. J., et al. 1993, PASP, 105, 1482
Shimajiri, Y., Kawabe, R., Takakuwa, S., et al. 2011, PASJ, 63, 105
Takakuwa, S., Saito, M., Lim, J., et al. 2012, ApJ, 754, 52
Tobin, J. J., Hartmann, L., Chiang, H.-F., et al. 2012, Natur, 492, 83
Tsukagoshi, T., Saito, M., Kitamura, Y., et al. 2011, ApJ, 726, 45
Whitney, B. A., Wood, K., Bjorkman, J. E., & Cohen, M. 2003, ApJ, 598, 1679
Wilson, G. W., Austermann, J. E., Perera, T. A., et al. 2008, MNRAS, 386, 807
Wilson, T. L., & Rood, R. 1994, ARA&A, 32, 191
Wu, J., Dunham, M. M., Evans, N. J., II, Bourke, T. L., & Young, C. H. 2007, AJ, 133, 1560
Wu, P.-F., Takakuwa, S., & Lim, J. 2009, ApJ, 698, 184
Zhou, S., Evans, N. J., II, Koempe, C., & Walmsley, C. M. 1993, ApJ, 404, 232