Substructures in the Disk-forming Region of the Class 0 Low-mass Protostellar Source
IRAS 16293–2422 Source A on a 10 au Scale

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Abstract

We have observed the Class 0 protostellar source IRAS 16293–2422 A in the C17O and H2CS lines as well as the 1.3 mm dust continuum with the Atacama Large Millimeter/submillimeter Array at an angular resolution of ~0′/1 (14 au). The continuum emission of the binary component, Source A, reveals the substructure consisting of five intensity peaks within 100 au from the protostar. The C17O emission mainly traces the circummultiple structure on a 300 au scale centered at the intensity centroid of the continuum, while it is very weak within a radius of 50 au from the centroid. The H2CS emission, by contrast, traces the rotating disk structure around one of the continuum peaks (A1). Therefore, it seems that the rotation centroid of the circummultiple structure is slightly different from that of the disk around A1. We derive the rotation temperature by using the multiple lines of H2CS. Approaching the protostar A1, the rotation temperature steeply rises up to 300 K or higher at the radius of 50 au from the protostar. It is likely due to a local accretion shock and/or the preferential protostellar heating of the transition zone from the circummultiple structure to the disk around A1. This position corresponds to the place where the organic molecular lines are reported to be enhanced. Since the rise of the rotation temperature of H2CS most likely represents the rise of the gas and dust temperatures, it would be related to the chemical characteristics of this prototypical hot corino.

Unified Astronomy Thesaurus concepts: Interstellar medium (847); Protostars (1302); Interstellar molecules (849); Interstellar emissions (840); Interstellar dynamics (839)

1. Introduction

Recently, rotationally supported disks have been found not only in Class I sources but also in some Class 0 sources (e.g., Murillo et al. 2013; Yen et al. 2013, 2017; Ohashi et al. 2014; Tobin et al. 2015, 2016b, 2016a; Seifried et al. 2016; Aso et al. 2017; Lee et al. 2017; Okoda et al. 2018). In spite of these extensive studies, there is still controversy regarding when and how a disk structure is formed around a newly born protostar. Moreover, the disk formation process has been revealed to be much more complicated for binary and multiple cases, both in observations (Dutrey et al. 2014; Tokuda et al. 2014; Takakuwa et al. 2014, 2017; Tobin et al. 2016b, 2016a; Boehler et al. 2017; Artur de la Villarmois et al. 2018; Alves et al. 2019) and in numerical simulations (e.g., Bate & Bonnell 1997; Kratter et al. 2008; Fateeva et al. 2011; Shi et al. 2012; Ragusa et al. 2017; Satsuka et al. 2017; Price et al. 2018; Matsumoto et al. 2019). For instance, circumbinary/circummultiple disk structures with a spiral structure as well as a circumstellar disk for each component are reported (e.g., Tobin et al. 2016a; Takakuwa et al. 2017; Artur de la Villarmois et al. 2018; Matsumoto et al. 2019; Alves et al. 2019). In addition, it is not clear how molecules are processed during the disk formation process and what kind of molecules are finally inherited by protoplanetary disks and potentially by planets. Understanding these processes is crucial, as they will provide important constraints on the initial physical and chemical conditions for the planetary system formation study. In this context, physical and chemical structures and their mutual relation for disk-forming regions of low-mass protostellar sources have been investigated with the Atacama Large Millimeter/submillimeter Array (ALMA; e.g., Sakai et al. 2014b, 2014a; Oya et al. 2016, 2017, 2018, 2019; Imai et al. 2016, 2019; Jacobsen et al. 2019). These studies reveal that infalling envelopes and rotationally supported disks are not smoothly connected to each other either in physical structure or in chemical composition, unlike previous expectations.

IRAS 16293–2422 is a well-studied low-mass protostellar source located in Ophiuchus (d ~ 140 pc; Ortiz-León et al. 2017). It is a Class 0 binary system, consisting of Source A and Source B, which are separated by 5′. Both of the components are famous for their richness in complex organic molecules (COMs) and are known as hot corinos (e.g., van Dishoeck et al. 1995; Schöier et al. 2002; Cazaux et al. 2003; Bottinelli et al. 2004; Ceccarelli 2004; Kuan et al. 2004; Chandler et al. 2005; Caux et al. 2011; Jørgensen et al. 2012). Recently, the chemical characteristics of Source B have been investigated extensively by the Protostellar Interferometric Line Survey (PILS) program with ALMA (e.g., Coutens et al. 2016; Jørgensen et al. 2016; Lykke et al. 2017; Manigand et al. 2020a). As well, the characteristics of Source A have recently been reported by Manigand et al. (2020b) in the same program. In addition, Source A was investigated in terms of the kinematic structures; the rotating signature of the gas surrounding the protostar was detected thanks to its nearly edge-on configuration (e.g., Pineda et al. 2012; Favre et al. 2014). Oya et al. (2016) reported that the kinematic structure of the gas in the vicinity of the protostar in Source A can be disentangled into the two major components: the infalling-rotating envelope and the rotating disk. They evaluated the protostellar mass (M = 0.75 M⊙) and the specific angular momentum of the infalling-rotating envelope (j = 1.3 \times 10^{-3} \text{ km s}^{-1} \text{ pc}) of this source assuming an inclination angle of 60° (0° for a face-on configuration). The transition from the infalling-rotating envelope to the rotating (Keplerian-like) disk was found to occur at the radius of 40–60 au from the center of gravity, which corresponds to the
radius of the centrifugal barrier of the infalling-rotating envelope. The chemical composition of the gas was found to change drastically in this transition zone.

The chemical evolution in protostellar sources is tightly related to the physical conditions, and especially, the gas temperature distribution in IRAS 16293–2422 has been modeled by Jacobsen et al. (2018); their 3D model of the dust and gas surrounding IRAS 16293–2422 Source A and Source B explains the observed distributions of the CO isotopologue lines and the dust emission. The gas dynamics connecting Source A and Source B has also been reported by van der Wiel et al. (2019). As for Source A, Oya et al. (2016) and van’t Hoff et al. (2020) derived the temperature structure on a 100–200 au scale by analyzing the intensity ratios of K-structure lines of H$_2$CS observed at a $0.05$ resolution ($\sim 70$ au). The result is discussed in relation to the drastic chemical change found on a 50 au scale mentioned above (Oya et al. 2016). Detailing a possible substructure in the transition zone is important for understanding the initial condition of the physical/chemical evolution in the disk formation process. However, the previous observations (Oya et al. 2016; van’t Hoff et al. 2020) do not have a sufficient spatial resolution ($\sim 0.5$; 70 au) for this purpose. In this study, we make use of the ALMA data observed at a high spatial resolution ($\sim 0.1$; 14 au) and take a close look at the disk/envelope structure of IRAS 16293–2422 Source A with particular focus on its substructure and gas temperature distribution. We note that Maureira et al. (2020) have very recently reported a high-resolution observation at 3 mm with ALMA, which can be compared with this study.

We summarize the observation in Section 2 and its overall results in Section 3. We present the kinematic structure of the gas around Source A in Section 4, and the gas temperature distribution in Section 5. Then, we discuss possible interpretations for the disk/envelope system of Source A in Section 6. The major conclusions are summarized in Section 7.

## 2. Observations

Our observations toward IRAS 16293–2422 were carried out on 2017 August 21 with ALMA during its Cycle 4 operation. Forty-four antennas were used in the observations. We employed the Band 6 receiver to observe the spectral lines of C$^{17}$O and H$_2$CS (Table 1). The field center of the observations was set to IRAS 16293–2422 Source A, which is located at $(\alpha_{ICRS}, \delta_{ICRS}) = (16^h53^m22.8713, -24^d28'36.5020)$. The baseline lengths of the antennas ranged from 21.0 m to 3696.9 m. The size of the field of view was $25''$15, and the typical size of the synthesized beam was $\sim 0.8''$1 for each image (see Table 1). The largest recoverable angular scale was $2''$27. The total on-source time was 70.6 min. Four spectral windows were observed. Their spectral resolution and the bandwidth are summarized in Table 2. The bandpass calibration was performed with J1517–2422, while the phase calibration was performed with J1625–2527 every 2 minutes. J1517–2422 and J1733–1304 were observed to derive the absolute flux density scale. The absolute accuracy of the flux calibration is expected to be better than 15% (ALMA Partnership et al. 2016).

The continuum and line images were obtained with the CLEAN algorithm. We employed the Briggs weighting with a robustness parameter of 0.5, unless otherwise noted. The 1.3 mm continuum image was prepared by averaging line-free channels, whose total frequency range was 0.3 GHz. The line maps were obtained after subtracting the continuum component directly from the visibility data. The line maps were resampled to make the channel width 0.2 km s$^{-1}$. A primary beam correction was applied to the continuum and the line maps. The rms noise level is 0.3 mJy beam$^{-1}$ for the continuum map, while it is 2.5 mJy beam$^{-1}$ and 2.0 mJy beam$^{-1}$ for the C$^{17}$O.

### Table 1

| Molecule | Transition | Rest Frequency (GHz) | $S_{\mu^2}$ ($D^2$) | $E_v$ (K) | Synthesized Beam Size |
|----------|------------|----------------------|---------------------|-----------|----------------------|
| 1.3 mm Continuum | | | | | |
| C$^{17}$O | J = 2–1 | 222.45–240.58 | 0.014 | 16 | $0.128 \times 0.080$ (P.A. −83°729) |
| H$_2$CS | $7_{0,7}$–$6_{0,6}$ | 224.714385 | 19.0 | 46 | $0.118 \times 0.077$ (P.A. −85°842) |
| | $7_{5,5}$–$6_{5,5}$ | 240.3820512 | 17.5 | 99 | $0.118 \times 0.079$ (P.A. −87°729) |
| | $7_{0,7}$–$6_{0,6}$ | 240.2668724 | 17.5 | 99 | $0.118 \times 0.079$ (P.A. −87°729) |
| | $7_{5,5}$–$6_{5,5}$ | 240.2619875 | 28.0 | 375 | $0.118 \times 0.077$ (P.A. −87°729) |

### Table 2

### Settings of the Spectral Windows in the Observation

| SPW ID | Frequency Range (GHz) | Resolution (kHz) | Molecular Lines |
|--------|-----------------------|------------------|-----------------|
| 0      | 240.2148020–240.4491915 | 61.039 | H$_2$CS ($7_{0,7}$–$6_{0,6}$), ($7_{1,6}$–$6_{2,5}$), ($7_{3,5}$–$6_{1,4}$), ($7_{4,4}$–$6_{1,3}$), ($7_{5,5}$–$6_{1,4}$), ($7_{5,5}$–$6_{2,4}$) |
| 1      | 240.5167470–240.5753444 | 15.260 | H$_2$CS ($7_{2,5}$–$6_{2,4}$) |
| 2      | 224.6885482–224.8057430 | 30.519 | C$^{17}$O ($J = 2–1$) |
| 3      | 222.4463399–223.3838980 | 488.311 | Continuum |
and H2CS line images, respectively. The velocity channel maps of the molecular lines were obtained by smoothing the velocity width of 1 km s\(^{-1}\) so that the rms noise level is 1.1 mJy beam\(^{-1}\) and 0.9 mJy beam\(^{-1}\) for the C17O and H2CS line images, respectively. We tried self-calibration in various ways. However, the images were not improved or even deteriorated. Since we discuss the proper motion of the continuum peaks, we employ the images without self-calibration in this paper.

### 3. Results

#### 3.1. 1.3 mm Continuum

Figure 1(a) shows the 1.3 mm dust continuum image of IRAS 16293–2422. The continuum emission of Source A extends along the northeast–southwest direction (Figure 1(b)). Its elongated shape suggests the nearly edge-on configuration of Source A (e.g., Huang et al. 2005). Moreover, it shows substructures. We identify five intensity peaks, as shown in Figure 1(b). Their positions and peak intensities are listed in Table 3. These values are obtained by using the 2D Fit Tool of casa viewer. Although IRAS 16293–2422 is known to have a bridge structure connecting Source A and Source B (e.g., Jørgensen et al. 2016; van der Wiel et al. 2019), such a structure is missing in our observation, probably due to the resolving-out effect in the interferometric observation.

In order to have a careful look at the clumpy structure of the 1.3 mm continuum emission, we clean the continuum image with a uniform weighting for a better spatial resolution. Figure 1(c) depicts the continuum image obtained with the uniform weighting. The angular resolution of the image with a uniform weighting is \(0.106 \times 0.064\) (\(\sim 14\) au \(\times 9\) au), which is slightly better than that with the Briggs weighting (\(0.128 \times 0.080\) (\(\sim 18\) au \(\times 11\) au). With the uniform weighting, the intensity peaks A1, A2, A3, and A4 are clearly resolved, as well as in Figure 1(b). In addition, the peak A1a, which is spatially separated from the nearby peak A1, is tentatively detected. Figure 1(d) shows the spatial profile of the continuum emission along the line passing the peaks A1 and A1a. The separation between A1 and A1a is clearer in the image with the uniform weighting. Although the uniform

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**Figure 1.** 1.3 mm continuum image. Panels (a) and (b) are obtained with the Briggs weighting with a robustness parameter of 0.5, while panel (c) is with uniform weighting (with a robustness parameter of \(-2.0\)). Contour levels in panel (a) are 10\(\sigma\), 20\(\sigma\), 40\(\sigma\), 80\(\sigma\), and 160\(\sigma\), where the rms noise level is 0.3 mJy beam\(^{-1}\). Contour levels in panels (b) and (c) are at intervals of 5\(\sigma\) starting from 5\(\sigma\), where the rms noise level is 0.3 mJy beam\(^{-1}\) and 0.2 mJy beam\(^{-1}\), respectively. Both the rms noise levels correspond to \(\sim 0.7\) K. Color scales in panels (b) and (c) are set to be from 0 K to \(\sim 70\) K.
weighting (Figure 1(c)) provides a slightly better resolution than the Briggs weighting (Figure 1(b)), the resolved-out effect increases due to a smaller contribution from short-baseline data. Because we are interested in the structure surrounding Source A, we hereafter employ the continuum image with the Briggs weighting (Figures 1(b)), which traces better the extended disk/envelope system.

The two continuum peaks in Source A (A1 and A2) were reported in the 2 cm (15 GHz) continuum image observed with the Very Large Array (VLA) by Wootten (1989). More clumpy features of Source A have recently been reported in the 2 cm (15 GHz) and 0.9 cm (33 GHz) continuum images observed with the VLA by Hernández-Gómez et al. (2019). Figures 2(a) and (b) show their centimeter continuum images overlaid on our millimeter continuum image. They reported the proper motion of these continuum peaks based on the VLA data obtained from 1986 to 2015 (Chandler et al. 2005; Pech et al. 2010), except for the peak A2b. Figure 2(c) shows the extrapolation of the proper motion from the VLA observation in 2014 February (2014.15) to our ALMA observation in 2017 August (2017.64). Although calibration errors in the observations may affect the peak positions, the continuum peaks A1 and A2 observed with VLA in 2014 seem to correspond to those observed with ALMA in 2017. Very recently, the proper motion of A1 and A2 was also discussed by Maureira et al. (2020).

It has been thought that Source A is a candidate of a multiple system based on its multiple outflow structures (e.g., Stark et al. 2004; Yeh et al. 2008; van der Wiel et al. 2019; Maureira et al. 2020). In fact, the continuum peaks A1 and A2 have been interpreted as protostars constituting a close binary system (Loinard et al. 2007; Pech et al. 2010; Hernández-Gómez et al. 2019), although A1 was also suggested to be a shock feature (Wootten 1989; Chandler et al. 2005). Meanwhile, the continuum peaks A2α and A2β observed with the VLA are interpreted as bipolar ejecta moving away from the protostar A2 (e.g., Hernández-Gómez et al. 2019). These two components (A2α and A2β) seem to be missing in our ALMA observation, considering their proper motion, although the continuum peak A3 detected with ALMA coincides with the A2β position observed in 2014 (Hernández-Gómez et al. 2019). The continuum peaks A3 and A4 (and A1a) detected with ALMA do not seem to have corresponding components in the VLA images. These peaks are not clearly seen in the 3 mm continuum image by Maureira et al. (2020), although a weak extended emission is seen around them. However, the peak A3 seems to correspond to Ab in the 1.3 mm continuum image reported by Sadavoy et al. (2018; see also Chen et al. 2013; Chandler et al. 2005). The nature of the continuum peaks will be discussed later (Sections 4.1 and 4.4).

### 3.2. Molecular Lines

In this observation, we detected various molecular lines as in the other observations toward this source (e.g., Jørgensen et al. 2016). Among them, we focus on the C17O and H2CS lines in this study to characterize the gas distribution and the temperature distribution. Their line parameters are summarized in Table 1. Figure 3 shows their integrated intensity maps.

#### 3.2.1. C17O

The distribution of the C17O ($J = 2–1$) line is extended along the distribution of the continuum emission over 300 au in diameter (Figure 3(a)). Although the signal-to-noise ratio of the integrated intensity map is not so high partly due to the resolved-out effect, the C17O emission seems to trace the outer region of the continuum distribution. Figure 3(b) shows the velocity map (moment 1 map) of the C17O line. The velocity gradient is clearly seen along the northeast–southwest direction; the emission is blueshifted in the northeastern side, while it is redshifted in the southwestern side. The velocity gradient is almost parallel to the elongation of the distribution of the continuum emission. It seems to trace the rotating motion, which is consistent with the previous works (e.g., Pineda et al. 2012; Favre et al. 2014; Oya et al. 2016).

Figure 4 shows the velocity channel maps of the C17O line. The C17O emission is detected with the confidence level of 10σ (11 mJy beam$^{-1}$) or higher for the velocity range from $-1$ km s$^{-1}$ to 9 km s$^{-1}$, or the velocity shift between $±5$ km s$^{-1}$ from the systemic velocity of 3.9 km s$^{-1}$. Additional emission features are seen in panels for the velocity range from $-8$ km s$^{-1}$ to $-2$ km s$^{-1}$ and from $13$ km s$^{-1}$ to 15 km s$^{-1}$. These are contaminations of the (CH$_3$)$_2$CO (18$_{6,13}$–17$_{6,12}$ EE and 18$_{6,13}$–17$_{5,12}$ EE at 224.700 GHz) transitions, the CH$_2$DOH (72,6–71,7, e1 at 224.701 GHz; 20,1,19–20,0,20, e1 at 224.725 GHz) lines, and/or an unidentified line. An absorption feature of the C17O line is seen around the systemic velocity, which is likely due to self-absorption by the cold foreground gas. As seen in the velocity map (Figure 3(b)), the rotation signature can be confirmed in the velocity channel maps.

| Peak | Peak Intensity (mJy beam$^{-1}$) | R.A. (ICRS) | Decl. (ICRS) |
|------|---------------------------------|-------------|--------------|
| A1   | 37.6                            | 16$^h$32$^m$22$^s$878 | $-24^\circ$28$^\prime$36$^\prime$691 |
| A1a  | 28.5                            | 16$^h$32$^m$22$^s$873 | $-24^\circ$28$^\prime$36$^\prime$785 |
| A1 (uniform weighting)$^b$ | 19.2                            | 16$^h$32$^m$22$^s$873 | $-24^\circ$28$^\prime$36$^\prime$827 |
| A2   | 22.4                            | 16$^h$32$^m$22$^s$852 | $-24^\circ$28$^\prime$36$^\prime$658 |
| A3   | 24.0                            | 16$^h$32$^m$22$^s$887 | $-24^\circ$28$^\prime$36$^\prime$496 |
| A4   | 20.4                            | 16$^h$32$^m$22$^s$846 | $-24^\circ$28$^\prime$36$^\prime$821 |
| Intensity centroid$^c$ |                                 | 16$^h$32$^m$22$^s$873 | $-24^\circ$28$^\prime$36$^\prime$614 |

Notes.

$^a$ Obtained from the continuum image with the Briggs weighting using the 2D Fit Tool of casa viewer.

$^b$ Obtained from the continuum image with uniform weighting. The beam size is 0$''$.106 $\times$ 0$''$.064 in this image.

$^c$ Obtained as the averaged position for the 3σ detection of the dust continuum emission in Source A. See Section 4.2.
3.2.2. H$_2$CS

Figures 3(c), (d), and (f) show the distributions of the H$_2$CS lines. We detected the six K-structure lines of H$_2$CS with the upper energy levels from 46 K to 375 K as listed in Table 1, although the highest K transitions ($7_5,2 - 6_5,1$, $7_5,3 - 6_5,2$) are contaminated with the $7_0,7 - 6_0,6$ line (see Section 4.4). All of the H$_2$CS line emissions show their intensity peak near the A1 continuum peak, in contrast to the C$^{17}$O ($J = 2 - 1$) line. Figure 3(e) shows the velocity map of the H$_2$CS ($7_2,5 - 6_2,4$) line. The velocity gradient due to the rotation is clearly seen as the C$^{17}$O line case.

Figure 5 shows the velocity channel maps of the H$_2$CS ($7_2,5 - 6_2,4$) line. Here, we employ this line because the low-excitation line ($7_{0,7} - 6_{0,6}$) is contaminated with the H$_2$CS ($7_{5,2} - 6_{5,1}$, $7_{5,3} - 6_{5,2}$) line (see Section 4.4). In contrast to the C$^{17}$O ($J = 2 - 1$) line case, a self-absorption feature is not seen near the systemic velocity. The H$_2$CS ($7_{2,5} - 6_{2,4}$) emission is detected with the confidence level of 10σ (9 mJy beam$^{-1}$) or higher for the velocity range from $-5$ km s$^{-1}$ to $+14$ km s$^{-1}$, or the velocity shift from $-9$ km s$^{-1}$ to $+10$ km s$^{-1}$. The velocity range is wider than that of the C$^{17}$O ($J = 2 - 1$) line. The high-velocity blueshifted emission is present on the northeastern side of A1, while the high-velocity redshifted emission is on the southwestern side. They likely trace the rotating motion around the protostar A1. That said, a clump is seen between the continuum peaks A2 and A4 in panels for the velocity from 8 km s$^{-1}$ to 12 km s$^{-1}$. This component can also be seen in the integrated intensity maps of the H$_2$CS lines as a shape of “tongue” from A1 (Figures 3(c), (d), (f)). It is highly redshifted near the continuum peak A4 in the velocity map (Figure 3(e)). We discuss this component in Sections 4.4.4 and 5.

4. Analysis and Discussion

4.1. Substructures of the 1.3 mm Continuum Emission

As described in Section 3.1, IRAS 16293–2422 Source A is a multiple system that includes at least two protostars A1 and A2 (Figure 1). Observational researches of binary and multiple systems have recently been reported (Tokuda et al. 2014; Takakuwa et al. 2014, 2017; Tobin et al. 2016b, 2016a;
Figure 3. Integrated intensity maps of the C$^{17}$O ($J = 2–1$; a) and H$_2$CS (c, d, and f) lines, and velocity maps (moment 1 maps) of the C$^{17}$O ($J = 2–1$; b) and H$_2$CS ($J_2,3-6_2,4$; e) lines. The velocity range for the integration is from $-2$ km s$^{-1}$ to $+10$ km s$^{-1}$ for the C$^{17}$O line (a, b) and from $-4$ km s$^{-1}$ to $+12$ km s$^{-1}$ for the H$_2$CS lines (c–f). These velocity ranges correspond to the velocity-shift ranges from $-6$ km s$^{-1}$ to $+6$ km s$^{-1}$ and from $-8$ km s$^{-1}$ to $+8$ km s$^{-1}$ with respect to the systemic velocity of Source A ($3.9$ km s$^{-1}$). Contours in each panel represent the 1.3 mm continuum. The contour levels are at intervals of 20$\sigma$ starting from 10$\sigma$, where the rms noise level is 0.3 mJy beam$^{-1}$. In panels (b) and (e), the moment 1 maps (color) are prepared for positions where the integrated intensity exceeds 3$\sigma$.

Figure 4. Velocity channel maps of the C$^{17}$O ($J = 2–1$) line. Each panel is prepared by averaging the velocity range of 1 km s$^{-1}$, while the line cube has a channel width of 0.2 km s$^{-1}$. Contours represent the 1.3 mm continuum map. For the contour levels, see the caption for Figure 3. The center velocity for each panel is shown in the upper-left corner, where the systemic velocity of Source A is 3.9 km s$^{-1}$. The panels for the velocity range from $-8$ km s$^{-1}$ to $-2$ km s$^{-1}$ and from 13 km s$^{-1}$ to 15 km s$^{-1}$ are affected by the contamination lines (see Section 3.2.1).
Boehler et al. 2017; Artur de la Villarmois et al. 2018; Alves et al. 2019. The radio continuum emission observed toward binary/multiple systems shows various substructures; for instance, L1551 NE has a circumstellar disk for each constituent of the binary and arm structures surrounding the binary system (Takakuwa et al. 2017), while [BHB2007] 11 has circumstellar disks connected to a circumbinary disk by spiral streamers (Alves et al. 2019). Numerical simulation studies for circumstellar disks indeed reproduce such substructures (e.g., Bate & Bonnell 1997; Fateeva et al. 2011; Satsuka et al. 2017; Price et al. 2018; Matsumoto et al. 2019).

Both the observational and theoretical research suggests a spatial gap of the gas distribution between the circumbinary disk and the circumstellar disks. These structures are thought to be caused by gravitational instability due to rotation and/or turbulence of a parent core (e.g., Bate et al. 2003; Matsumoto & Hanawa 2003; Lim et al. 2016).

In Figure 2, the 1.3 mm continuum emission traces substructures similar to those observed previously with VLA (Hernández-Gómez et al. 2019). The weak extended component on a 300 au scale shown in Figure 1(b) seems to be a circumbinary/circummultiple envelope or disk, while each protostar inside it may be associated with a circumstellar disk revealed by a local emission peak. Our current observation does not show an apparent spiral or arm structure which may exist in the circummultiple structure, although the continuum peak A1a that is extended from A1 may be a hint of such inner structures. In the following sections, we investigate the physical and kinematic structures of the circummultiple structure and possible circumstellar disks.

4.2. Morphological Structure of the Disk/Envelope System

The overall distribution of the 1.3 mm dust continuum emission in Source A looks like an ellipse (Figure 1), whose major axis extends along the northeast–southwest direction. It is necessary to define the center position and the major and minor axes of the distribution in order to investigate the kinematic structure of the gas showing the rotation signature. However, this process is not straightforward, because the dust continuum distribution has substructures. Therefore, we derive them in the following way. First, we determine the centroid of the continuum intensity distribution using the data points with a $3\sigma (0.9 \text{ mJy beam}^{-1})$ detection or higher to be the following:

\[
(\alpha_{\text{ICRS}}, \delta_{\text{ICRS}}) = (16h32m22.873, -24\degree28\arcmin36.614).
\]

Figure 6(a). Then, we fit the positions of the data points used above to an ellipse by using the least-squares method weighted by the intensity at each position. The centroid of the ellipse is found to coincide with the intensity centroid obtained above within the pixel size of the map (0\".025). The major and minor axes are derived in the above fit to be 1\".25 (~170 au) and 0\".50 (~70 au), respectively, while the position angle (P.A.) of the major axis of the elliptic distribution to be 50°2. This ellipse is shown in Figure 6(a). Therefore, we assume that the mid-plane of the disk/envelope system extends along the P.A. of 50° (hereafter “the envelope mid-plane direction”). If a flat disk structure without thickness is assumed, its inclination angle is roughly estimated to be 66° (0° for a face-on configuration) from the ratio of the sizes of the major and minor axes. This value can be regarded as a lower limit to the
The Astrophysical Journal, 904:185 (32pp), 2020 December 1

...inclination angle if a finite thickness and a round shape for the disk structure are considered. Thus, the disk/envelope system of IRAS 16293–2422 Source A is confirmed to be nearly or almost edge-on as reported previously (e.g., Pineda et al. 2012; Favre et al. 2014; Oya et al. 2016). The envelope mid-plane direction and the intensity centroid determined above are shown in Figure 6(a) by a white arrow and a black cross, respectively. The intensity centroid can be regarded as a rough estimate of the center of gravity for the elliptic structure, assuming that the intensity of the dust emission is proportional to the dust mass at each position.

Figure 7(a) shows the spatial profiles of the continuum intensity and the integrated intensities of the molecular lines along the envelope mid-plane direction. The continuum emission shows a peak at the angular offset of 0° (the intensity centroid of the continuum emission), which corresponds to the skirt of the A1 peak. It also has an additional peak at the angular offset of +0°3 (~40 au), which corresponds to that of the A3 peak. Similarly, the H2CS (7_{0,7}–6_{0,6}, 7_{2,5}–6_{0,4}, 7_{4,3}–6_{4,2}, 7_{4,4}–6_{4,3}) emissions have a peak at the angular offset of 0° with a shoulder or another peak at the offset of 0°/2. Therefore, these emissions are centrally concentrated. In contrast, the C17O (J = 2–1) emission is more extended than the continuum and the H2CS emissions and shows a double-peaked feature with a depression of its intensity in the area inward of 50 au from the centroid (the interior of the two dotted lines in Figure 7(a)), where the continuum and the H2CS emissions are the brightest.

4.3. Kinematic Structure of the C17O Line

We first focus on the double-peaked distribution of the C17O (J = 2–1) emission and analyze its kinematic structure. Figure 8 shows the position–velocity (PV) diagrams of the C17O line prepared along the six directions shown by arrows in the attached velocity map, which are centered at the intensity centroid of the continuum emission. In the PV diagram along the envelope mid-plane direction (Figure 8(a)), we see the spin-up feature toward the intensity centroid of the continuum emission; the velocity gets more blueshifted from the systemic velocity (3.9 km s−1) approaching the protostar position from the southwestern side, while it gets more blueshifted approaching from the northeastern side. Interestingly, this feature almost vanishes inward of 0°/4 (~50 au) from the continuum peak position. This corresponds to the position where the integrated intensity of the C17O line decreases (Section 4.2; Figure 7(a)).

We also inspected the velocity structure of the C17O line around the continuum peak A1 as in the case of the H2CS lines, which will be described in Section 4.4. We found that the C17O emission does not show a symmetric feature around A1 in contrast to what is seen in Figure 8. Therefore, we concluded that the center for the kinematic structure of the C17O emission should be at the center of gravity of the elliptic structure traced by the dust continuum emission, rather than at A1.

In this section, we compare the observed kinematic structure with two simple models that have often been used in previous studies. Here, we use 3D models of a flat disk/envelope with the Keplerian motion or the infalling-rotating motion. The details for these models are reported by Oya et al. (2014), Oya (2017), and Y. Oya & S. Yamamoto (2020, in preparation). In these models, the line emission is assumed to be optically thin, and the radiation transfer is not considered. Free parameters are the protostellar mass and the inclination angle for the Keplerian model, while the infalling-rotating envelope model has the radius of the centrifugal barrier as a free parameter in addition to them. We conduct the chi-squared (χ2) test for the two models to obtain reasonable parameters. The details for the reduced χ2 test are...
The best-fit and reasonable ranges for the parameters are summarized in Table 4. The best-fit and reasonable ranges for the parameters are summarized in Table 4. The best-fit and reasonable ranges for the parameters are summarized in Table 4.

4.3.1. Keplerian Model for the C$^{17}$O Line

First, we examine the Keplerian model for the PV diagrams of C$^{17}$O. We optimize the protostellar mass and the inclination angle as free parameters to explain the observed PV diagrams. Although the reduced $\chi^2$ values suffer from the imperfection of the model and the complexity of the sources, we obtain the following best-fit parameters of the Keplerian model: the central mass is 2.0 $M_\odot$ and the inclination angle is 70°, as shown in Table 4. Here, the inner and outer radii of the model are fixed to be 50 au and 300 au according to the observed molecular distribution. Other details of the fittings are described in Appendix B.

Figure 8 shows the PV diagrams of the Keplerian model with the best-fit parameters. As depicted in Figure 8(a), the PV diagram along the envelope mid-plane direction is reasonably reproduced. However, the PV diagrams along the other directions are not well explained, although their overall trend is roughly reproduced (Figures 8(b)–(f)). The resolved-out effect and/or the self-absorption effect would affect the velocity components near the systemic velocity ($3.9 \text{ km s}^{-1}$); the observation does not show emission, but the model does. However, there are some parts in the PV diagrams where the line emission is detected but not reproduced by the model. Such a discrepancy originates from the imperfection of the model. For instance, the model cannot explain well the PV diagram along the direction perpendicular to the envelope mid-plane direction (Figure 8(d)). The blueshifted component in Figure 8(d) has a higher velocity shift in the observation than the model.
4.3.2. Infalling-rotating Envelope Model for the C$^{17}$O Line

Next, we examine the infalling-rotating envelope model (Oya et al. 2014). In this model, the velocity field is approximated by the ballistic motion. The energy and specific angular momentum of the gas is assumed to be conserved, and therefore the gas cannot fall inward of the periastron, which is called the “centrifugal barrier.” The following best-fit parameters for the infalling-rotating envelope model are obtained: the protostellar mass is 1.0 $M_e$, and the inclination angle is 80°. The radius of the centrifugal barrier and the outer radius of the model are fixed to be 50 au and 300 au according to the observed molecular distribution. The results for the fittings are described in Appendix B.

Figure 8 shows the PV diagrams of the infalling-rotating envelope model with the best-fit parameters. As in the case of the Keplerian disk model described above, the infalling-rotating envelope model does not explain the observed kinematic structure very well, either; for instance, the velocity shift in the model is larger than in the observed kinematic structure in Figures 9(c), (d), and (e). The PV diagrams along the envelope mid-plane direction is reasonably reproduced. However, the redshifted component of the C$^{17}$O ($J = 2–1$) line seems to suffer severely from the absorption effect by the infalling gas, so that a velocity gradient due to the infall motion that is expected along the direction perpendicular to the envelope mid-plane direction in the model is not evident in Figure 9(d).

4.3.3. Circummultiple Structure

Neither of the two simple models fully explains the detailed kinematic structure because of the complexity of the source. This source has small substructures, which are now resolved in our observation. Hence, the kinetic structure would be too complicated to be modeled by these simple models. Although the infalling-rotating envelope model gives smaller $\chi^2$ values than does the Keplerian model (Tables 5 and 6), it would be too
Table 4
Physical Parameters Derived in the Model Analyses

| Parameters                      | Keplerian Model | IRE Model$^a$ | Keplerian Model | IRE Model$^a$ |
|--------------------------------|-----------------|---------------|-----------------|---------------|
| Center of gravity$^b$          | Intensity centroid of the continuum emission | Continuum peak A1 |                 |               |
| Coordinates (ICRS) of the center of gravity | R.A.: 16°32′22.873, decl.: −24°28′36.614 | R.A.: 16°32′22.878, decl.: −24°28′36.961 |                 |               |
| Position angle$^c$             | 50°             | 50°           | 50°             | 50°           |
| Systemic velocity              | 3.9 km s$^{-1}$ | 3.9 km s$^{-1}$ | 2.5 km s$^{-1}$ | 2.5 km s$^{-1}$ |
| Inclination angle$^d$          | 70° (reasonable range: 66°–90°) | 80° (reasonable range: 70°–90°) | 60° (reasonable range: 40°–70°) | 70° (reasonable range: 60°–90°) |
| Central mass$^e$               | 2.0 $M_\odot$ (1.5 $M_\odot$–2.5 $M_\odot$) | 1.0 $M_\odot$ (0.6 $M_\odot$–1.2 $M_\odot$) | 0.4 $M_\odot$ (0.4 $M_\odot$–0.8 $M_\odot$) | 0.20 $M_\odot$ (0.15 $M_\odot$–0.25 $M_\odot$) |
| Radius of the CB$^f$           | ...             | 50 au         | ...             | 10 au          |
| Inner radius                   | 50 au           | 50 au         | 0.56 au (1 pixel) | 10 au          |
| Outer radius$^g$               | 300 au          | 300 au        | 30 au           | 30 au          |
| Minimum $\chi^2$/DOF           | 3.38            | 2.18          | 7.07            | 8.98           |
| Figures                        | 8, 18           | 9, 19         | 10, 20, 21, 22  | 23, 24, 25    |

Notes.
$a$ Infalling-rotating envelope model.
$^b$ See Figure 6.
$^c$ The position angle of the direction along which the disk/envelope system extends.
$^d$ An angle of 0° for a face-on configuration. The values in the parentheses show the reasonable range of the inclination angle obtained by the reduced $\chi^2$ test (Tables 5–8) and the distribution of the continuum emission (see Section 4.2).
$^e$ Note that the central mass and the inclination angle are correlated with each other: the central mass is approximately scaled by $\frac{\sin^2 i}{\sin^2 i}$, where $i$ is the inclination angle (0° for a face-on configuration). The values in the parentheses show the reasonable range of the central mass obtained by the reduced $\chi^2$ test (Tables 5–8).
$^f$ Radius of the centrifugal barrier of an infalling-rotating envelope.
$^g$ The emissivity at the radius larger than this radius from the center of gravity is assumed to be zero in the models.

hasty to conclude that the C$^{17}$O emission comes from an infalling-rotating envelope. We can reasonably constrain the central mass of Source A from the kinematic structure observed at the 0′′1 resolution. Finer tuning of the model by, for instance, combining the two simple models is practically difficult, because such an analysis includes too many free parameters for our current observational data of this source, and it is beyond the scope of this work.

We compare the protostellar masses derived above with those in the literature. The protostellar mass of Source A is reported to be from 0.5 $M_\odot$ to 1.0 $M_\odot$ (e.g., Looney et al. 2000; Bottinelli et al. 2004; Huang et al. 2005; Caux et al. 2011; Pineda et al. 2012; Favre et al. 2014; Oya et al. 2016), while Takakuwa et al. (2007) and Maureira et al. (2020) reported a larger central mass from 0.5 $M_\odot$ to 2.0 $M_\odot$. The central mass employed for the infalling-rotating envelope model above (1.0 $M_\odot$) is consistent with most of the previous reports. Meanwhile, the mass employed for the Keplerian model (2.0 $M_\odot$) agrees with the highest end of the previous reports.

As mentioned in Section 1, Oya et al. (2016) reported the infalling-rotating envelope structure with a radius of 300 au around Source A in the OCS emission at an angular resolution of 0′′65 × 0′′51. They suggested that the gas outside of a radius of 50 au from the center of gravity is an infalling-rotating envelope, while that inside a radius of 50 au is the Keplerian disk. If the C$^{17}$O gas has the Keplerian motion rather than the infalling-rotating motion, the C$^{17}$O gas would have a different kinematic structure from the OCS gas at a radius ranging from 50 au to 300 au from the continuum intensity centroid, although the angular resolution of the OCS observation is coarser than that of the C$^{17}$O observation. Therefore, the OCS distribution could be somewhat different from the C$^{17}$O distribution. For instance, if the envelope gas falls onto a thin rotating disk diagonally from above and below the mid-plane (e.g., Figures 4.5 and 4.11 in Hartmann 2009), the OCS ($J = 19–18$) line with the high upper-state energy (111 K) will preferentially trace a warm surface of the infalling envelope gas. By contrast, the C$^{17}$O ($J = 2–1$) line with the upper-state energy of 16 K tends to trace a cold dense mid-plane of the rotating disk, whose motion is close to be Keplerian.

The C$^{17}$O emission seems to trace the circumstellar structure in Source A and is deficient in the vicinity of the center of gravity. A circumbinary disk is previously observed for L1448-IRS3B by Tobin et al. (2016a) in the 13CO ($J = 2–1$) emission with ALMA. Meanwhile, a hole in the 13CO distribution tracing the rotating gas was previously reported for TMC-1A by Harsono et al. (2011) and Maureira et al. (2016). They interpreted the hole structure as absorption of the 13CO emission by the optically thick dust. Meanwhile, theoretical simulations show a gap in the gas distribution between a circumbinary disk and circumstellar disks (e.g., Bate & Bonnell 1997; Fateeva et al. 2011; Satsuka et al. 2017; Price et al. 2018; Matsumoto et al. 2019). At first glance, such a gap/hole structure would not be the case for the C$^{17}$O emission in IRAS 16293–2422 Source A; in the C$^{17}$O
de deficient area, the dust is not expected to be so optically thick as to significantly suppress the molecular emission, because the H₂CS emission is observed there (Figure 3). However, an optically thick dust may cause the depression of the C¹⁷O emission if the molecular distribution is different between CO and H₂CS (see the next section for details).
4.3.4. $^{13}$O Deficiency within 50 au

The weak $^{13}$CO ($J = 2–1$) emission near the centroid of the continuum emission (Figures 3(a) and 7(a)) is difficult to interpret as being caused by the freezing out of CO onto dust grains. In this area, the gas temperature is expected to be much higher than the desorption temperature of CO (20 K), according to the analysis of the H$_2$CS line (see Section 5). If the dust temperature is also as high as the gas temperature, the weak emission of the C$^{13}$O ($J = 2–1$) line cannot be simply attributed to the adsorption of CO onto dust grains.

The adsorption of CO might be the case, if the disk mid-plane temperature within 50 au were lower than the adsorption temperature of CO. That said, the H$_2$CS emission would mainly come from the warm region including the disk surface, and the effect of the depletion in the disk mid-plane could be less important. This picture qualitatively explains the behavior of the spatial profiles shown in Figure 7(a).

If such different distributions between CO and H$_2$CS are the case, the optical depth effect of the continuum emission affects the C$^{13}$O emission more seriously than the H$_2$CS emissions. The C$^{13}$O emission from the cold and dense mid-plane would be depressed by an optically thick dust, while the H$_2$CS emissions from the warm surface region would be less affected. Such an effect of the optically thick dust was invoked for the $^{13}$CO hole observed in TMC-1A by Harsono et al. (2018).

The excitation effect can cause the weak C$^{13}$O emission in the hot region in the vicinity of the continuum peak A1. In Figure 7(b), the integrated intensity is 49 mJy beam$^{-1}$ km s$^{-1}$ (120 K km s$^{-1}$) and less than 3$\sigma$ (21 mJy beam$^{-1}$ km s$^{-1}$; 51 K km s$^{-1}$) at its peak and near A1, respectively. If the column density were the same for these two positions, the difference between these integrated intensities would be explained by a factor of three difference of the excitation temperature (i.e., 100 K and 300 K for these two positions). Here, the local thermodynamic equilibrium (LTE) condition and the optically thin condition are assumed. In this case, the excitation temperature would change sharply with distance from the protostar, as the intensity of the C$^{13}$O emission changes sharply.

Alternatively, nonvolatile organic molecules formed in the gas phase of the disk component are adsorbed onto dust grains, which may result in the exhaustion of carbon from the gas phase (Aikawa et al. 1996). This might eventually cause a deficiency of CO. In fact, IRAS 16293–2422 Source A is known to be rich in COMs. Moreover, Oya et al. (2016) reported that the COM emission is enhanced within a radius of 50 au, where the CO emission is weak in this observation. The deficiency in CO may be related to such peculiar chemical characteristics.

4.4. Kinematic Structure of the H$_2$CS Lines

4.4.1. Rotating Disk around A1

In contrast to the C$^{13}$O line, the H$_2$CS lines are concentrated within the radius of 50 au (Figures 3(c), (d), and (f)). In order to investigate this feature, we prepare the integrated intensity maps of the H$_2$CS ($J=2–1$) line for the blue- and redshifted velocity ranges (Figure 6(b)). Note that this line is free from significant contamination by other lines according to the spectral line database (JPL and CDMS; Pickett et al. 1998; Müller et al. 2005; Endres et al. 2016), which is also confirmed in the actual observations by van’t Hoff et al. (2020) and this work. Figure 6(b) shows the high velocity-shift components with a velocity shift from $\pm 4$ km s$^{-1}$ to $\pm 8$ km s$^{-1}$. The rotation motion can be recognized around the continuum peak A1 rather than the intensity centroid of the dust continuum, although an additional redshifted component is seen near the continuum peak A4. The blueshifted and redshifted components overlap just at the continuum peak A1. This result indicates the rotating structure associated with A1. Since the disk/envelope system of Source A shows substructures in its continuum emission, the center of gravity could be different between the envelope and this rotating structure. By focusing on the vicinity of A1, the P.A. of the velocity gradient due to the rotation is evaluated to be 50$^\circ$. Therefore we assume that the mid-plane of the rotating structure around A1 extends along this P.A., which is parallel to the envelope mid-plane direction derived from the dust continuum distribution (Section 4.2). This direction (hereafter “the disk mid-plane direction”) is shown by a red arrow in Figure 6(b). Figure 7(b) shows the spatial profiles of the continuum emission and the integrated intensities of the molecular lines along the disk mid-plane direction. The continuum emission and the H$_2$CS emission are concentrated to the continuum peak A1, while the C$^{13}$O emission shows a double-peaked feature, as shown by the spatial profiles along the envelope mid-plane direction (Figure 7(a))

4.4.2. Keplerian Model for the H$_2$CS Line

First, we perform the $\chi^2$ test for the Keplerian model and the H$_2$CS ($J=4–3$) line, as for the C$^{13}$O case in Section 4.3.1 (see also Appendix A). We obtain the following best-fit parameters: the central mass is $0.4 M_\odot$ and the inclination angle is 60$^\circ$, where the systemic velocity is 2.5 km s$^{-1}$. The inner and outer radii of the model are fixed to be $\sim 30$ au and 30 au according to the observed molecular distribution, respectively. We regard the emission extending over 30 au as a part of the circummultiple structure traced by the C$^{13}$O emission (Section 4.3), and we do not take them into account in the following analysis. The best-fit and the reasonable ranges for the parameters are summarized in Table 4. Other details for the fittings are described in Appendix C.

Figure 10 shows the PV diagrams of the H$_2$CS ($J=4–3$) line along the directions with P.A. of 50$^\circ$ and 80$^\circ$ centered at the protostar A1. The Keplerian model results with the best-fit parameters obtained above are overlaid on the observation results. The PV diagrams of the H$_2$CS ($J=4–3$) line along all of the directions shown by the black arrows in the velocity map (moment 1 map) on the top left panel are shown in Appendix C (see Figure 22). We see the high velocity-shift components concentrated to the protostar A1. The PV diagrams in Figure 10 as well as those in Figure 22 can be reasonably explained by the Keplerian model described above, except for the three features particularly seen in Figures 10(b) and (d); (see Section 4.4.4).

4.4.3. Infalling-rotating Envelope Model for the H$_2$CS Line

Next, we perform the $\chi^2$ test for the infalling-rotating envelope model and the H$_2$CS ($J=4–3$) line, as for the C$^{13}$O case in Section 4.3.2. We obtain the following best-fit parameters: the central mass is $0.2 M_\odot$, and the inclination angle is 70$^\circ$, where the systemic velocity is 2.5 km s$^{-1}$. The outer radius of the model is fixed to be 50 au according to the
observed molecular distribution. The best-fit and the reasonable ranges for the parameters are summarized in Table 4. Other details for the fittings are described in Appendix C. We find that the kinematic structure traced by H$_2$CS is more poorly reproduced by the infalling-rotating envelope model than by the Keplerian model (Table 4; see Figure 25). Therefore, the observed kinematic structure would prefer the Keplerian motion.

4.4.4. Comments on Additional Features

According to the model analysis in Sections 4.4.2 and 4.4.3, it is most likely that the continuum peak A1 is a protostellar source associated with a rotating disk structure. Some components detected in the H$_2$CS emission are not attributed to this rotating disk structure. Figures 10(a) and (c) show low velocity-shift components extended from the angular offset of $\pm 0''/2$ to $\pm 1''$. As we have described in Section 4.4.2, this component can be attributed to the circummultiple structure traced by the C$^{17}$O emission (Figures 8, 9). Moreover, the observed PV diagrams show three features spilling over the model results, as we mentioned in Section 4.4.2.

An excess of emission is seen at the velocity of about 12 km s$^{-1}$ toward the A1 position (zero offset) in the PV diagram of the H$_2$CS ($J_{12}=6_{2,1}$) line ("Excess 1" in Figures 10(a), (b)). Since this feature is not seen in the H$_2$CS ($J_{4,4}=6_{4,3}$) line, it would have suffered from this contamination by the unresolved doublet of H$_2$CS ($J_{4,4}=6_{4,3}$, $J_{5,3}=6_{5,2}$). Although Oya et al. (2016) suggested an existence of the Keplerian disk component based on the observation of the H$_2$CS ($J_{0,7}=6_{0,6}$) line, it would have suffered from this contamination (see also van’t Hoff et al. 2020). The H$_2$CS ($J_{2,5}=6_{2,4}$) line shows a weak emission ("Excess 2") near Excess 1, too. Since it has a slight offset from the A1 position, it may be a contamination by another molecular line rather than a high
velocity-shift component of the H$_2$CS ($^{72,5}$--$^{62,4}$) line in the vicinity of the protostar. The peak intensity of this weak contamination is less than 30\% of that of the H$_2$CS ($^{72,5}$--$^{62,4}$) line, and moreover, it is separated from the H$_2$CS ($^{72,5}$--$^{62,4}$) line along the velocity axis. Therefore, the H$_2$CS ($^{72,5}$--$^{62,4}$) line is verified to have no significant contamination by other molecular lines in its PV diagrams (Figures 10(c), (d)), as noted in the previous sections. As well, this weak contamination does not affect the discussion for the rotation temperature of the H$_2$CS in Section 5. Thus, we can certainly confirm the disk component with this line. It should be noted that the detection of the high-excitation line of H$_2$CS (a composite of $^{75,2}$--$^{65,1}$, $^{75,3}$--$^{65,2}$; $E_u = 375$ K) suggests a high gas temperature of the disk component near the protostar A1.

Another excess emission feature in Figure 10(b) is the high-velocity component at an offset of $-0^\circ 5$ from A1 (“Excess 3”). This component can be seen in the H$_2$CS ($^{72,5}$--$^{62,4}$, $^{74,3}$--$^{64,2}$, $^{74,4}$--$^{64,3}$) lines (Figures 10(d), (f)), and cannot be ascribed to contamination by other lines. This component is neither the infalling-rotating envelope described in Section 4.3 nor the disk component around A1. It likely represents the component extended through the midpoint between A2 and A4 (see Section 3.2.2). This feature is interesting, because the velocity increases with increasing distance from the protostar A1 (Figure 3(e); see the $v = 7$–12 km s$^{-1}$ panels of Figure 5). It might be a part of the outflowing motion. Alternatively, it looks like a part of a spiral structure (Figure 3(f)), as seen in circumbinary systems (Takakuwa et al. 2014, 2017; Matsumoto et al. 2019; Alves et al. 2019). Further characterization of this component is left for future study.

4.4.4. Comparison between the Circumstellar and Circummultiple Structures

We have also examined a possible disk structure associated with the other continuum peaks. For instance, Figure 11 shows the PV diagrams of the H$_2$CS ($^{74,3}$--$^{64,2}$, $^{74,4}$--$^{64,3}$) line, where the position axes are centered at the protostar A2. If a molecular line traces a possible disk associated to A2, the PV diagrams have to be symmetric with respect to the A2 position and the systemic velocity of A2 (2.5 km s$^{-1}$), for reference.

Figure 11. Position–velocity diagrams of the H$_2$CS ($^{74,3}$--$^{64,2}$, $^{74,4}$--$^{64,3}$: color) line. The left panel shows the velocity maps of the H$_2$CS ($^{72,5}$--$^{62,4}$) line, which is the same as in Figure 3(e). Black arrows in the velocity map represent the position axes along which the PV diagrams are prepared, which are centered at the continuum peak A2. Vertical white dashed lines represent the position of A2. Horizontal white dashed lines represent the systemic velocity assumed for the disk associated to A1 (2.5 km s$^{-1}$), for reference.
Figure 11. One may think that the kinematic structure in the panel (a); (P.A. of 50°) showing a velocity gradient can be interpreted as Keplerian motion with a systemic velocity of ∼6 km s$^{-1}$. In fact, Maureira et al. (2020) have recently suggested the existence of a rotating disk structure associated with the protostar A2. However, it is more adequately interpreted as a part of other components, i.e., the disk associated to A1 or the circummultiple structure of Source A in our observational result. At the current stage, we cannot conclude whether a rotating disk structure exists around the protostar A2. As well as the protostar A2, we have investigated the kinematic structure in the vicinity of the continuum peaks A3 and A4. Our current observation does not show a rotating disk structure around either of them.

Although the physical parameters in Table 4 are obtained with the simplified models, it is worth noting that the best-fit masses, inclination angles, and systemic velocities are different between the circummultiple structure of Source A traced by the C$^{18}$O ($J = 2 - 1$) emission and the circumstellar structure of the protostar A1 traced by the H$_2$CS ($7_{4,3}$–$6_{2,2}$, $7_{4,4}$–$6_{4,3}$) emission. First, the central mass estimated for the circummultiple structure ranges from 1.5 $M_\odot$ to 2.5 $M_\odot$, with the Keplerian model and from 0.6 $M_\odot$ to 1.2 $M_\odot$ with the infalling-rotating envelope model. These values are larger than the central mass ranges from 0.4 $M_\odot$ to 0.8 $M_\odot$ (the Keplerian model) and from 0.15 $M_\odot$ to 0.25 $M_\odot$ (the infalling-rotating envelope model) estimated for the circumstellar structure around A1. The circummultiple structure surrounds other possible components (A2, A3, A4, and A1a), as well as the protostar A1, and also their possible circumstellar structures. Therefore, the central mass evaluated from the kinematic structure of the circummultiple structure should be higher than the mass evaluated for A1.

Maureira et al. (2020) have recently reported that the gas mass is (1–3) $\times$ 10$^{-3}$ $M_\odot$, (1–3) $\times$ 10$^{-3}$ $M_\odot$, and 0.03–0.1 $M_\odot$ for the substructure around A1, that around A2, and the extended structure surrounding both of them, respectively, based on the 3 mm continuum emission. These values are significantly smaller than the difference between measures of the central mass determined from the circummultiple and circumstellar structures found in this study. Therefore, the masses of the rest of the sources, i.e., the protostar A2 and possible protostars A3 and A4, would contribute to the kinematic structure of the circummultiple structure.

Also, the inclination angle seems larger for the circummultiple structure than for the circumstellar structure, although it has a large uncertainty. A1 is likely one component of a potential binary/multiple system of Source A. Therefore, the differences of the inclination angle and the systemic velocity imply that the rotating disk structure around A1 could be tilted with respect to the circummultiple structure of Source A. As well, the difference of the systemic velocity between the two models, 3.9 km s$^{-1}$ for the circummultiple structure and 2.5 km s$^{-1}$ for the circumstellar structure, implies a potential motion for the protostar A1 in Source A.

5. Distribution of the Rotation Temperature of H$_2$CS

In this section, we investigate the temperature distribution using the high spatial resolution data of H$_2$CS. So far, the temperature structure on a 100–200 au scale has been studied by Oya et al. (2016) and van’t Hoff et al. (2020) using the $K$-structure lines of H$_2$CS observed at a 70 au resolution. The rotation temperature derived from these lines is a good measure of the gas kinetic temperature, because the radiation processes between the different $K_e$ levels ($\Delta K_e = \pm 2, \pm 4$) are very slow. Hence, they can be used for delineating the temperature structure around the protostar. Oya et al. (2016) derived the rotation temperature at the five positions with offsets of $\pm 1\arcsec$, $\pm 0\arcsec.5$, and 0\arcsec from the continuum peak position, which correspond to the envelope, the transition zone (centrifugal barrier), and the disk, respectively, using the intensity of the $7_{0,7}$–$6_{0,6}$, $7_{2,5}$–$6_{2,4}$, and $7_{4,4}$–$6_{4,3}$ lines integrated over the velocity range corresponding to each component. Based on the result, they suggested the presence of a temperature rise at the transition zone by comparison of the temperatures at the five positions and discussed the result in relation to the enhancement of COMs near the transition zone. Later, van’t Hoff et al. (2020) observed more H$_2$CS lines to derive the temperature structure of this source. They used the peak fluxes instead of the integrated intensity to derive the line ratio and delineate the temperature distribution in Source A. The temperature profile along the direction of the disk/envelope system does not reveal the local temperature rise suggested by Oya et al. (2016). Therefore, they interpreted the temperature profile in terms of the radiation heating from the protostar. Although these works reveal the fundamental temperature distribution of this source, the spatial resolution is too coarse to examine the temperature structure around the transition zone in detail. Since substructures in the circummultiple system of Source A are now evident, we revisit the temperature structure of this source with the high-resolution H$_2$CS data. Here, we employ the H$_2$CS ($7_{2,5}$–$6_{2,4}$) and ($7_{4,3}$–$6_{4,2}$, $7_{4,4}$–$6_{4,3}$) lines for the analysis, because the H$_2$CS ($7_{0,7}$–$6_{0,6}$) line suffers from contamination by the H$_2$CS ($7_{2,5}$–$6_{5,1}$, $7_{5,3}$–$6_{5,2}$) lines, as we describe in Section 4.4.4, the weak contamination for the H$_2$CS ($7_{4,3}$–$6_{4,2}$, $7_{4,4}$–$6_{4,3}$) is confirmed to have no significant contamination in the molecular line database and in this observation (Figure 11), as for the H$_2$CS ($7_{2,5}$–$6_{2,4}$) line case mentioned in Section 4.4.4.

Figure 12(a) shows the distribution of the ratio of the integrated intensity of the H$_2$CS ($7_{4,3}$–$6_{4,2}$, $7_{4,4}$–$6_{4,3}$) line relative to that of the H$_2$CS ($7_{2,5}$–$6_{2,4}$) line, while Figure 12(b) shows the distribution of the rotation temperature of H$_2$CS calculated from the integrated intensity ratio. Figures 13(a) and 14(a) show the spatial profiles of the integrated intensity ratio and the rotation temperature along the disk mid-plane direction (a red arrow in Figure 6(b)), respectively. Here, we assume the LTE condition and the optically thin conditions for the two lines. The LTE condition for H$_2$CS is well fulfilled in this hot and dense region, as revealed with the non-LTE calculation by Oya et al. (2016). In order to verify the optically thin condition, we roughly calculate the optical depths of the H$_2$CS ($7_{2,5}$–$6_{2,4}$) and ($7_{4,3}$–$6_{4,2}$, $7_{4,4}$–$6_{4,3}$) lines from the observed brightness temperature and the derived rotation temperature. Here, we ignore the contribution of the dust emission, because the treatment of this effect requires detailed radiation transfer and is beyond the scope of this paper. The derived optical depths are mostly lower than 0.5, and the median value is 0.28 and 0.10 for the H$_2$CS ($7_{2,5}$–$6_{2,4}$) and ($7_{4,3}$–$6_{4,2}$, $7_{4,4}$–$6_{4,3}$) lines, respectively. The optical depth of the H$_2$CS ($7_{2,5}$–$6_{2,4}$) line exceeds 1 for some parts. However, such high optical depth
parts are in the low-temperature regions (<100 K). Since we discuss the temperature structure of hot components around the protostar, the optical depth effect does not seriously affect our conclusions. The rotation temperature of H$_2$CS derived from the $^{7}_{2,5}$–$^{6}_{2,4}$ and $^{7}_{4,3}$–$^{6}_{4,2}/^{7}_{4,4}$–$^{6}_{4,3}$ lines is confirmed to be consistent with the gas kinetic temperature derived using the RADEX code (van der Tak et al. 2007) with the H$_2$ density range of $10^{7}$–$9$ cm$^{-3}$, which is relevant to disk/envelope systems (Oya et al. 2016).

The rotation temperature of H$_2$CS is evaluated to be as high as 300 K near A1. A high rotation temperature area is extended from A1 to southwestern part (Figure 12(b)). The rotation temperature apparently decreases with increasing distance from the protostar A1 position with a slight enhancement at the southwest part. These features are consistent with the result obtained at a lower spatial resolution by van’t Hoff et al. (2020). It is worth noting that the tongue-like feature from A1 (Section 3.2.2) shows a high temperature (>200 K; Figure 12(b)). As discussed in Section 4.4, this might be related to the outflowing motion.

We have also derived the rotation temperature from the intensity ratio of the $^{7}_{2,5}$–$^{6}_{2,4}$ line to the $^{7}_{0,7}$–$^{6}_{0,6}$ line for reference. The temperature is generally lower than that derived from the $^{7}_{2,5}$–$^{6}_{2,4}$ and $^{7}_{4,3}$–$^{6}_{4,2}/^{7}_{4,4}$–$^{6}_{4,3}$ lines. For instance, the former is 100 K and the latter is 200 K at the continuum peak A3. This is probably because the $^{7}_{0,7}$–$^{6}_{0,6}$ line would sample colder regions and is partly contaminated by the H$_2$CS ($^{7}_{5,2}$–$^{6}_{5,1}$, $^{7}_{5,3}$–$^{6}_{5,2}$) line (Section 4.4.4). Hence, we use the rotation temperature derived from the $^{7}_{2,5}$–$^{6}_{2,4}$ and $^{7}_{4,3}$–$^{6}_{4,2}/^{7}_{4,4}$–$^{6}_{4,3}$ lines in the following discussions.

Figure 15 shows the velocity channel maps of the rotation temperature of H$_2$CS. Each map is derived using the intensity ratio of the velocity channel maps of the H$_2$CS ($^{7}_{2,5}$–$^{6}_{2,4}$) and ($^{7}_{4,3}$–$^{6}_{4,2}$, $^{7}_{4,4}$–$^{6}_{4,3}$) lines. As in Figure 12(b), the optically thin conditions for the two lines and the LTE condition are assumed. In Figure 12, the envelope and disk components are contaminated with each other along the line of sight, because the line emission is integrated along the velocity axis. However, they are expected to be disentangled to some extent in the velocity channel maps. In Figure 15, the rotation temperature of H$_2$CS apparently becomes higher approaching to the protostar A1 position. It is as high as 400 K near A1.

In the panels for the velocities of $-3$ km s$^{-1}$ and $+11$ km s$^{-1}$ of Figure 15, the rotation temperature is as high as ~400 K at some positions apart from the protostar A1. These positions roughly correspond to the positions within which the C$^{18}$O emission decreases. Figures 16(a) and (b) show the maps of the highest intensity ratio of the two H$_2$CS lines and the highest rotation temperature along the velocity channels, which are derived from the cube data. In other words, the maximum values along the line of sight are shown in these maps. These maps are obtained by using the immoments task of casa with the option “moments = [8].” Figure 13(b) shows their spatial profiles along the disk mid-plane direction. The maximum intensity ratio along the line of sight increases steeply at a distance of 50 au from the protostar A1, and is almost constant within this radius. The highest rotation temperature along the line of sight shown in Figure 14(b) also increases steeply at the same position but shows a large scatter within it. It should be noted that very high temperatures obtained at some positions are artificial. Since the intensity ratio at these positions are close to the high-temperature limit (1.47 for $T = \infty$), as shown in Figure 13(b), the derived temperature is sensitive to a small change in the ratio and suffers from a large error. Therefore, the intensity ratio itself better represents the temperature profile. Interestingly, the positions of the steep increase correspond to the transition zone from the circummultiple structure to the circumstellar structure, as mentioned above.

Therefore, the local rise of the rotation temperature seems to occur near the transition zone from the circummultiple structure of Source A to the circumstellar structure of the protostar A1. A hint of such a temperature rise in the transition zone was previously suggested by Oya et al. (2016). However, this previous report would have been just fortuitous based on the results for a few positions, given the detailed analysis by van’t Hoff et al. (2020). Now, our high-resolution observation (~0.1") indeed reveals a sharp change in the temperature. The local rise of the rotation temperature of H$_2$CS most likely reflects the local rise of the gas temperature. Candidate
mechanisms causing a local temperature rise are discussed in Section 6.

6. Transition from the Envelope to the Disk-forming Region

When the radiation heating by the central protostar (A1) is considered as a heating source, the gas temperature is expected to gradually decrease as a power law of the distance to the protostar. In the edge-on case, the maximum gas temperature along the line of sight is expected to do so as well (Figure 17(a)). If the protostars other than A1 could contribute to the heating, the temperature profile would be more gentle than in the case of heating by only A1. This effect may contribute to flatten the temperature profile around A1 within the radius of 50 au. Nevertheless, it seems difficult to explain the local steep rise of the temperature on both the northeastern and southwestern sides of A1 by protostellar heating alone. Therefore, another heating mechanism is expected in IRAS 16293–2422 Source A.

The peak temperature profile projected onto the plane of the sky is expected to be flat if the actual radial temperature profile is flat as well, or if it has a local rise in a ring-like structure. The

Figure 13. (a) Spatial profile of the ratio of the integrated intensity of the H$_2$CS (74,3–64,2, 74,4–64,3) line relative to the H$_2$CS (73,5–63,4) line. (b) Spatial profile of the peak value of the intensity ratio of the H$_2$CS (74,3–64,2, 74,4–64,3) line relative to the H$_2$CS (73,5–63,4) line. The position axes are along the disk mid-plane direction, which is shown by a red arrow in Figure 6(b); (Section 4.4.1). The colored areas represent the error ranges; for instance, the lower limit for the integrated intensity ratio in panel a is taken as $(I_4 - \sigma)/(I_3 + \sigma)$, where $I_3$ and $I_4$ are the integrated intensities of the H$_2$CS (74,3–64,2, 74,4–64,3) and (73,5–63,4) lines and $\sigma$ stands for their rms noise level (6 mJy beam$^{-1}$ km s$^{-1}$). The rms noise level for the integrated intensity used in panel a is 6 mJy beam$^{-1}$ km s$^{-1}$, while that for the line intensities used in panel b is 2 mJy beam$^{-1}$. The red horizontal line in panel b represents the high-temperature limit (1.47 for $T = \infty$).
observed temperature profile, which shows a steep rise around 50 au and then flattens, requires that the temperature is not significantly higher in the vicinity of the protostar than at the distance of 50 au from the protostar due to some mechanism. The temperature is expected naturally to increase approaching the protostar due to radiation heating, and therefore, a completely flat temperature profile within a radius of 50 au is unlikely. It seems more likely that the radial temperature profile has an increase at a radius of 50 au, drops just inside it, and gradually increases approaching to the protostar.

If the local temperature rise just outside of the circumstellar structure of A1 occurs due to an accretion shock by the infalling gas, it will appear in a ring-like structure surrounding the disk structure (Figure 17(b)). In fact, the model study by Fateeva et al. (2011) shows that bow shocks can occur near the inner edge of a circumbinary disk. It may heat up the innermost edge of the circumstellar structure in IRAS 16293–2422 Source A. In the edge-on or nearly edge-on case, the maximum gas temperature along the line of sight is expected to show a flat feature as a function of distance from the protostar (A1).
This corresponds to what can be seen in Figures 13(b) and 14(b).

Such a gas temperature distribution with a ring-like structure is also caused by a physical structure of the gas; the stagnated gas in the transition zone from the circummultiple structure to the circumstellar structure can be piled up vertically to the mid-plane of the disk, and the gas is efficiently heated up by the radiation from the protostar without the shielding by the circumstellar disk structure (Figure 17(b)). In any case, the distribution of the rotation temperature in IRAS 16293–2422 Source A shown in Figure 16(b) seems to be consistent with the picture of a hot ring-like region.

The picture of a hot ring-like region would also be related to the local enhancement of the COM emission reported by
Oya et al. (2016). The CH$_3$OH emission and the HCOOCH$_3$ emission likely come from the ring-like region with a radius of 50 au surrounding the protostar, based on their kinematic structures. According to Oya et al. (2016), the COM emission seems weaker in the circumstellar disk structure than at the transition zone. Although the spatial resolution of their observation is insufficient to explore this, such a distribution could be caused by the temperature distribution shown in Figure 17. The kinematic structures of the C$^{17}$O and H$_2$CS lines are consistent with those previously observed at centimeter wavelengths, if their proper motions are considered. They also agree with a recent report on the 3 mm continuum emission. We detect new continuum peaks (A3, A4, and A1a). Meanwhile, A2α and A2β observed at centimeter wavelengths, which are thought to be the ejecta from A2, are missing. Therefore, IRAS 16293–2422 Source A is likely a multiple system.

The C$^{17}$O ($J = 2−1$) line emission traces the rotating gas on a 300 au scale centered at the intensity centroid of the dust continuum emission. However, C$^{17}$O is found to be deficient within a radius of 50 au from the intensity centroid of the continuum emission. Enhancement of the temperature, depletion of CO onto dust grains in the mid-plane of the disk/envelope structure, and exhaustion of carbon to nonvolatile organic molecules can be considered as the origin of this feature.

The multiple lines of H$_2$CS mainly trace the disk component around the strongest continuum peak (A1). Even the high-excitation lines ($7_{5,2}$–$6_{5,1}$, $7_{5,3}$–$6_{5,2}$; $E_u = 375$ K) are detected. The 1.3 mm continuum emission traces the nearly edge-on disk/envelope system. Moreover, the substructures on a 0.′5 (<100 au) scale are resolved, and five continuum peaks are identified. The expected profile of the maximum gas temperature along the line of sight is schematically shown for each situation, assuming that the system has an almost edge-on configuration. This profile can be qualitatively compared to Figures 14(b) and 16(b) in the observation.

7. Summary

We have observed the Class 0 low-mass protostellar source IRAS 16293–2422 Source A in the C$^{17}$O and H$_2$CS lines as well as in the 1.3 mm dust continuum at a high angular resolution of ∼0′′1 (14 au). The major findings are as follows:

1. The 1.3 mm continuum emission traces the nearly edge-on disk/envelope system. Moreover, the substructures on a 0.′5 (<100 au) scale are resolved, and five continuum peaks are identified. The positions of two continuum peaks (A1 and A2) are consistent with those previously observed at centimeter wavelengths, if their proper motions are considered. They also agree with a recent report on the 3 mm continuum emission. We also detect new continuum peaks (A3, A4, and A1a). Meanwhile, A2α and A2β observed at centimeter wavelengths, which are thought to be the ejecta from A2, are missing. Therefore, IRAS 16293–2422 Source A is likely a multiple system.

2. The C$^{17}$O ($J = 2−1$) line emission traces the rotating gas on a 300 au scale centered at the intensity centroid of the dust continuum emission. However, C$^{17}$O is found to be deficient within a radius of 50 au from the intensity centroid of the continuum emission. Enhancement of the temperature, depletion of CO onto dust grains in the midplane of the disk/envelope structure, and exhaustion of carbon to nonvolatile organic molecules can be considered as the origin of this feature.

3. The multiple lines of H$_2$CS mainly trace the disk component around the strongest continuum peak (A1). Even the high-excitation lines ($7_{5,2}$–$6_{5,1}$, $7_{5,3}$–$6_{5,2}$; $E_u = 375$ K) are detected.

4. The kinematic structures of the C$^{17}$O and H$_2$CS lines are examined by a Keplerian model and an infalling-rotating
envelope model. The center of gravity, the inclination angle, and the systemic velocity of the circummultiples structure of Source A traced by C17O are possibly different from those of the circumstellar structure around the protostar A1 traced by H2CS.

(5) The distribution of the rotation temperature of H2CS is derived. In an overall view, the rotation temperature increases approaching the protostar A1, as usually expected for the gas temperature profile determined by radiation heating from the protostar. Interestingly, the rotation temperature shows a steep rise around the transition zone from the circummultiples structure to the circumstellar disk associated to the protostar A1. This local steep rise could be attributed to a possible accretion shock by the infalling gas and/or the thermal heating of the stagnated gas by the protostar. If the dust temperature rises there as well, it would be related to the rich COM emission, which is the chemical characteristic of IRAS 16293–2422 Source A. The “hot corino” may have a ring-like structure, instead of a simple spherical or disk-like structure.

While theoretical works have progressed extensively regarding the study of disk formation (e.g., Hennebelle & Ciardi 2009; Li et al. 2011; Machida et al. 2011; Tomida et al. 2015; Tsukamoto et al. 2017; Lam et al. 2019), observational studies tend to have lagged behind them due to limited high-resolution observations. Recently, radio observational studies have revealed the fundamental picture of the infalling-rotating envelope and the disk inside it, thanks to the unprecedented angular resolution and the sensitivity of millimeter and submillimeter interferometers including ALMA. This work demonstrates that the transition zone from the circummultiples disk/envelope to the circumstellar disk is not smooth. Moreover, even substructures of the disk-forming region are now within the scope of observations. Further study of these issues will provide us with deep insight into the formation process of the disk and also the chemical evolution in that process.

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Appendix A
Reduced Chi-squared Test for the Position–Velocity Diagrams

In Sections 4.3 and 4.4, we conduct the chi-squared (χ2) test for the observed PV diagrams and the model results. We calculate the reduced χ2 value (χ2/DOF), which is the sum of the square of the difference between the modeled and observed PV diagrams along the envelope mid-plane direction at each pixel normalized by the square of the rms in the observation (2.5 mJy beam−1 for C17O and 2.0 mJy beam−1 for H2CS). A large reduced χ2 value originates mainly from the complexity of the source and the imperfection of the model. Hence, we should take relatively large ranges of the parameters that can reasonably reproduce the observed features. Based on this thought, the parameter ranges are determined from the range where the reduced χ2 value increases by 1. The best-fit and the reasonable ranges for the parameters derived by the χ2 test are summarized in Table 4.

Appendix B
Analysis of C17O

Since the C17O emission notably suffers from the self-absorption effect, we use only the blueshifted component from −3 km s−1 to +3 km s−1 to calculate χ2. Table 5 shows the reduced χ2 values for the central mass versus the inclination angle plane. Figure 18 shows examples of the PV diagrams of the Keplerian model overlaid on the C17O observation. We confirm the inclination angle from 40° to 90° to be the reasonable range for the Keplerian model. We also consider

| Central Mass (M⊙) |
|------------------|
| Inclination Angle (°) |
| 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 | 3.5 | 4.0 |
| 90 | 5.84 | 5.14 | 4.32 | 4.26 | 5.78 | 7.80 | 9.42 | 10.64 |
| 80 | 5.82 | 5.16 | 4.34 | 4.26 | 5.47 | 7.45 | 9.25 | 10.53 |
| 70 | 5.61 | 4.65 | 3.80 | 3.70 | 5.47 | 7.47 | 9.27 | 10.92 |
| 60 | 5.65 | 4.85 | 3.95 | 3.85 | 5.47 | 7.52 | 9.28 | 10.53 |
| 50 | 5.84 | 5.25 | 4.71 | 4.62 | 5.22 | 7.49 | 9.44 | 10.53 |
| 40 | 6.10 | 5.56 | 5.11 | 4.70 | 4.54 | 5.22 | 7.30 | 10.53 |
| 30 | 6.42 | 5.94 | 5.62 | 4.59 | 5.07 | 4.83 | 4.73 | 4.56 |

Notes.

* The infalling-rotating envelope models are compared with the PV diagram of the C17O (J = 2−1) line. The PV diagram is prepared along the envelope mid-plane direction (P.A. 50°), which is centered at the intensity centroid of the continuum emission. The pixels with the angular offset from 0° to +2° and the velocity from −3 km s−1 to +3 km s−1 are taken into account. A total of 2480 pixels are used for the calculation. The minimum value is highlighted by a double box. Single boxes highlight values whose difference from the minimum value is lower than 1.

b An angle of 0° for a face-on configuration.
the lower limit of the inclination angle of 66° obtained from the distribution of the continuum emission (Section 4.2), and therefore the reasonable range for the inclination angle is from 66° to 90°. Then, we confirm the central mass from 1.5 $M_\odot$ to 2.5 $M_\odot$ to be the reasonable range for the Keplerian model. It should be noted that the protostellar mass and the inclination angle of 60°, 70°, and 80°.

Figure 18. Position–velocity diagrams of the C$^{17}$O ($J = 2–1$; color) line and the results of the Keplerian disk model (contour). Position axes in the panels are shown by arrows in Figure 8, which are centered at the intensity centroid of the continuum emission. The color maps are the same as those in Figure 8. The physical parameters employed for the models are: a central mass of 1.0 $M_\odot$, 2.0 $M_\odot$, and 3.0 $M_\odot$, and an inclination angle of 60°, 70°, and 80°. Other details of the model are given in the caption of Figure 8. Contour levels for the model result are at intervals of 10% of the peak intensity in the model cube.

### Table 6

| Central Mass ($M_\odot$) | Inclination Angleb (°) | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 |
|--------------------------|------------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 90                       | 5.77                   | 4.45| 3.19| 2.37| 2.24| 2.24| 2.67| 3.51| 4.90| 6.72| 8.78|
| 80                       | 5.79                   | 4.49| 3.19| 2.36| 2.18| 2.18| 2.55| 3.34| 4.67| 6.42| 8.41|
| 70                       | 5.73                   | 4.77| 3.85| 3.24| 3.02| 3.02| 3.39| 4.16| 5.25| 10.59|16.56|
| 60                       | 5.91                   | 5.25| 4.60| 4.11| 3.85| 4.12| 4.82| 5.85| 7.19| 8.81|
| 50                       | 6.09                   | 5.55| 5.10| 4.71| 4.36| 4.12| 4.17| 4.51| 4.98| 5.56|
| 40                       | 6.30                   | 5.83| 5.51| 5.20| 4.86| 4.58| 4.40| 4.20| 4.13| 4.25|
| 30                       | 6.48                   | 6.24| 5.88| 5.66| 5.46| 5.21| 4.96| 4.83| 4.62| 4.47|

Notes.

- The infalling-rotating envelope models are compared with the PV diagram of the C$^{17}$O ($J = 2–1$) line. The PV diagram is prepared along the envelope mid-plane direction (P.A. 50°), which is centered at the intensity centroid of the continuum emission. The pixels with angular offsets from 0° to +2° and velocities ranging from $-3 \, \text{km} \, \text{s}^{-1}$ to $+3 \, \text{km} \, \text{s}^{-1}$ are taken into account. A total of 2480 pixels are used for the calculation. The minimum value is highlighted by a double box. Single boxes highlight values whose difference from the minimum value is lower than 1.

- An angle of 0° for a face-on configuration.

The Astrophysical Journal, 904:185 (32pp), 2020 December 1 Oya & Yamamoto
angle are correlated with each other, as shown by the boxes in Table 5.

Like the Keplerian model analysis described above, we also investigate the infalling-rotating envelope model with the two variable parameters (the central mass and the inclination angle) to explain the observations by using the $\chi^2$ test. The radius of the centrifugal barrier and the outer radius of the model are fixed to be 50 au and 300 au based on the observed distribution. Table 6 shows the results of the reduced $\chi^2$ test for the central mass versus inclination angle plane. Figure 19 shows examples of the PV diagrams of the infalling-rotating envelope model overlaid on the C$^{17}$O observation. We confirm the protostellar mass from 0.6 $M_\odot$ to 1.2 $M_\odot$ and the inclination angle from 70° to 90° to be the reasonable ranges for the parameters of the infalling-rotating envelope model.

Appendix C
Analysis of H$_2$CS

In contrast to the C$^{17}$O analysis, we use the two PV diagrams of the H$_2$CS (7$_{4,3}$-6$_{3,2}$, 7$_{4,3}$-6$_{4,3}$) line prepared along the disk mid-plane direction (P.A. 50°) and the direction perpendicular to it (P.A. 140°), and use both the red- and blueshifted components with a velocity range of $-6$ km s$^{-1}$ to $+11$ km s$^{-1}$.

The results for the Keplerian model are summarized in Table 7. Figures 20 and 21 show examples of the model results for the PV diagrams along and perpendicular to the disk mid-plane direction, respectively. The reasonable ranges for the parameters are: a central mass within 0.4 $M_\odot$ to 0.8 $M_\odot$ and an inclination angle within 40° to 70°. Here, we assume the systemic velocity of 2.5 km s$^{-1}$ and an outer radius of 30 au.
Figure 22 shows the model results with the best-fit parameters overlaid on the observed PV diagrams of the H₂CS line \((7_{4,5}^{+} - 6_{4,6}^{+}, 7_{4,4}^{+} - 6_{4,3}^{+})\) prepared for various directions. The results for the infalling-rotating envelope model are summarized in Table 8. Figures 23 and 24 show some examples of the model results for the PV diagrams along and perpendicular to the disk mid-plane direction, respectively. The reasonable ranges for the parameters are: a central mass within 0.15 \(M_\odot\) to 0.25 \(M_\odot\) and an inclination angle within 60° to 90°. The radius of the centrifugal barrier is varied from 5 au to 20 au. Here, we assume a systemic velocity of 2.5 km s\(^{-1}\) and an outer radius of 30 au. Figure 25 shows the model results with the best-fit parameters overlaid on the observed PV diagrams of the H₂CS line \((7_{4,5}^{+} - 6_{4,6}^{+}, 7_{4,4}^{+} - 6_{4,3}^{+})\) prepared for various directions. The observed PV diagram along the disk mid-plane direction (P.A. 50°; Figure 25(a)) seems reasonably reproduced by the infalling-rotating envelope model, as in the case of the Keplerian model.
However, some diagrams are less well reproduced by the infalling-rotating envelope model than by the Keplerian model. For instance, the observational result in Figure 25(b) shows a velocity gradient where the red- and blueshifted components are on the southwestern and the northeastern sides of the protostar A1, respectively. The infalling-rotating envelope model does not...
explain this observed trend well, while the Keplerian model does (Figures 10(f) and 22(b)). In fact, the reduced \( \chi^2 \) value is larger for the fit by the infalling-rotating envelope model than for the fit by the Keplerian model (Tables 7 and 8). Therefore, the observed kinematic structure is better described as Keplerian motion than as infalling-rotating motion.

Figure 21. Same as Figure 20, but along the direction perpendicular to the disk mid-plane direction (P.A. 140°).
Figure 22. Position–velocity diagrams of the H$_2$CS ($7_{4,3}$–$6_{4,2}$, $7_{4,4}$–$6_{4,3}$; color) line and the Keplerian disk model (contour). Position axes in the panels are shown by arrows in Figure 10, which are centered at the continuum peak A1. Black contours represent the same Keplerian model as in Figure 10. The parameters employed for the model are the same as those in Figures 10 and 20. Contour levels for the model results are at intervals of 10% of the peak intensity in the model cube.
Figure 23. Same as Figure 20, but for the infalling-rotating envelope model. Black contours represent the infalling-rotating envelope model results. The physical parameters employed for the model are: a central mass of $0.1 M_\odot$, $0.2 M_\odot$, and $0.3 M_\odot$, and an inclination angle of $50^\circ$, $70^\circ$, and $90^\circ$. The emissivity in the model is assumed to be proportional to $r^{-1.5}$, where $r$ denotes the distance from the center of gravity, and is zero for $r > 30$ au. The scale height of the disk is assumed to increase with increasing distance from the center of gravity with the flared angle of $30^\circ$. Contour levels for the model result are at intervals of 10% of the peak intensity in the model cube. The dashed contours in panels for the inclination angle of $80^\circ$ and $90^\circ$ represent the dip toward the central position.
Figure 24. Same as Figure 23, but along the direction perpendicular to the disk mid-plane direction (P.A. 140°).
Figure 25. Same as Figure 22, but for the infalling-rotating envelope model. The physical parameters employed for the model are: a central mass of $0.20 \, M_\odot$, an inclination angle of $70^\circ$, and a radius of the centrifugal barrier of 10 au. Other details of the model are given in the caption of Figure 25. Contour levels for the model result are at intervals of 10% of the peak intensity in the model cube. The dashed contours in panel (a) represent the dip toward the central position.
