Early Planet Formation in Embedded Disks (eDisk). V. Possible Annular Substructure in a Circumstellar Disk in the Ced110 IRS4 System

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Early Planet Formation in Embedded Disks (eDisk). V. Possible Annular Substructure in a Circumstellar Disk in the Ced110 IRS4 System

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Abstract

We have observed the Class 0/I protostellar system Ced110 IRS4 at an angular resolution of $0.05\arcsec$ ($\sim 10 \text{ au}$) as part of the Atacama Large Millimeter/submillimeter Array large program, Early Planet Formation in Embedded Disks. The 1.3 mm dust continuum emission reveals that Ced110 IRS4 is a binary system with a projected separation of $\sim 250 \text{ au}$. The continuum emissions associated with the main source and its companion, named Ced110 IRS4A and IRS4B, respectively, exhibit disk-like shapes and likely arise from dust disks around the protostars. The continuum emission around Ced110 IRS4A has a radius of $\sim 110 \text{ au}$ ($\sim 0.06\text{ mas}$) and shows bumps along its major axis with an asymmetry. The bumps can be interpreted as a shallow, ring-like structure at a radius of $\sim 40 \text{ au}$ ($\sim 0.2\text{mas}$) in the continuum emission, as demonstrated from two-dimensional intensity distribution models. A rotation curve analysis on the $^{12}\text{C}^{16}\text{O}$ and $^{13}\text{CO} J = 2-1$ lines reveals the presence of a Keplerian disk within a radius of $120 \text{ au}$ around Ced110 IRS4A, which supports the interpretation that the dust continuum emission arises from a disk. The ring-like structure in the dust continuum emission might indicate a possible annular substructure in the surface density of the embedded disk, although the possibility that it is an apparent structure due to the optically thick continuum emission cannot be ruled out.

Unified Astronomy Thesaurus concepts: Planet formation (1241); Star formation (1569); Low mass stars (2050); Protoplanetary disks (1300); Protostars (1302); Young stellar objects (1834); Millimeter astronomy (1061)

1. Introduction

Protoplanetary disks ubiquitously form as part of the star formation process (e.g., Terebey et al. 1984) and are the future sites of planet formation. Recent observations at an angular resolution of $\sim 5 \text{ au}$ with the Atacama Millimeter/submillimeter Array (ALMA) have revealed that most disks around Class II sources exhibit substructures such as rings and gaps (e.g., ALMA Partnership et al. 2015; Long et al. 2018 a; Andrews et al. 2018; Bi et al. 2020). Several mechanisms have been proposed to explain these substructures (Flock et al. 2015; Zhang et al. 2015; Okuzumi et al. 2016; Takahashi et al. 2016), including a scenario in which these substructures are created by protoplanets through disk–planet interaction (Lin & Papaloizou 1986; Takeuchi et al. 1996; Pinilla et al. 2012; Zhu et al. 2012). Indeed, some observations have reported evidence of protoplanets present within disks (Kepler et al. 2018; Haffert et al. 2019; Benisty et al. 2021; Currie et al. 2022), suggesting that disk–planet interaction could commonly take place in substructured disks.
The progress in characterizing planet formation within disks raises the question of when planet formation within disks begins. It has been suggested that protoplanetary disks around Class II sources are not massive enough to form gas giant planets (e.g., Manara et al. 2018), although the masses of the protoplanetary disks could be underestimated by ignoring the effects of dust scattering (Carrasco-González et al. 2019; Liu 2019; Zhu et al. 2019; Ueda et al. 2020). On the other hand, observations toward younger disks around Class 0 and I protostars, which are still embedded in surrounding envelopes, have shown that the embedded disks have sufficient mass to enable giant planet formation without the need for unrealistically high efficiency of planet formation (Tychoniec et al. 2018; Tobin et al. 2020). Moreover, several embedded disks exhibit substructures (Sheehan & Eisner 2017, 2018; Teague et al. 2019; Segura-Cox et al. 2020; Sheehan et al. 2020; Ohashi et al. 2022), which could be a more direct signature of planet formation. However, how common such substructures are among embedded disks is still unclear as few protostars have been imaged on scales of ~5–10 au.

In this paper, we report observations of the protostellar system Ced110 IRS4 at an angular resolution of 0′′05 (~10 au) in the dust continuum and molecular lines, as part of the ALMA large program, Early Planet Formation in Embedded Disks (eDisk; Ohashi et al. 2023). Ced110 IRS4 is a Class 0/I protostellar system in the Cederblad (Ced) 110 region of the Chamaeleon (Cha) I dark cloud. Its bolometric temperature and luminosity are 68 K and 1.0 L☉, respectively (Ohashi et al. 2023), classifying this source as a Class 0 protostar, while it has been considered as a Class I source in previous works (Zinnecker et al. 1999; Pontoppidan & Dullemond 2005). Thus, this source may be near the division of the Class 0 and I phases, although it should be noted that the classification of Class 0 and I with a boundary of the bolometric temperature of 70 K (Chen et al. 1995; Evans et al. 2009) is somewhat arbitrary and not based on any particular physical change in the system. The Ced110 region is clustered and possesses eight young stellar objects (YSOs) within ~0.2 pc (Prusti et al. 1991; Lehtinen et al. 2001; Persi et al. 2001). Molecular line observations with single-dish telescopes have revealed a high-velocity outflow, which is thought to be driven from Ced110 IRS4, although the launching point was not spatially resolved (Prusti et al. 1991; Hiramatsu et al. 2007). A reflection nebula extending in the north–south direction is associated with the protostar and the presence of an edge-on disk was suggested from the shadow around the reflection nebula (Zinnecker et al. 1999; Pontoppidan & Dullemond 2005). The distance to Ced110 IRS4 is not well constrained, as it is not directly detected by Gaia. While several works reported slightly different distances to the Cha dark cloud of 179–210 pc (Dzib et al. 2018; Roccatagliata et al. 2018; Voirtin et al. 2018; Zucker et al. 2019, 2020; Galli et al. 2021), the most precise measurement using Gaia Data Release (DR) 2 was provided by Galli et al. (2021), considering both statistical and systematic errors. They reported two different stellar populations at distances of 191.4 and 186.7 pc in the Cha I dark cloud. We adopt their measurement of the mean distance to the entire Cha I of 189 pc in this paper, as the two populations spatially overlap and which group Ced110 IRS4 belongs to is uncertain. We also adopt a systemic velocity of 4.67 km s⁻¹ derived in this work (Section 4) for the Ced110 IRS4 system throughout this paper.

The outline of this paper is as follows. The details of the observations are summarized in Section 2 and the immediate results in Section 3. Analyses of the dust continuum and molecular line emissions are presented in Section 4. The implications of the observational results and analyses are discussed in Section 5. Finally, we summarize the conclusions of the paper in Section 6.

2. ALMA Observations

Ced110 IRS4 was observed during ALMA’s Cycles 7 and 8 at ALMA Band 6 with antenna configurations of C-5 and C-8, as a part of the ALMA large program eDisk (2019.1.00261.L: PI N. Ohashi). The observations consisted of four execution blocks (EBs), whose details are summarized in Table 1. CO isotopologues, SO, and other lines were observed in the frequency division mode (FDM), and the 1.3 mm (225 GHz) continuum emission was obtained from the line-free channels of the spectral windows with a maximum window width of 1.875 GHz. The phase center was set to (R.A., decl.) = (11°06′46″:440, −77°22′32″/20) for observations of the target source. The shortest projected baseline was 15.1 m, providing a sensitivity to extended structures such that 10% of the total emission at 225 GHz extending to ~11″ is recovered (Wilner & Welch 1994). The main target lines and final velocity resolutions of reduced maps are summarized in Table 2. Further details of the observations including the full spectral setup are presented by Ohashi et al. (2023).

All data were reduced with the Common Astronomy Software Applications (CASA; McMullin et al. 2007) package version 6.2.1. The details of the imaging procedure can be found in Ohashi et al. (2023). In summary, we conducted ALMA standard calibration through the ALMA pipeline, and then performed phase and amplitude self-calibration for the 1.3 mm continuum emission until the signal-to-noise ratio (S/N) was not improved. The gain tables obtained by the self-calibration were also applied to line data. All images were produced using the tclean task with clean masks determined by the automasking algorithm. Clean components were drawn down to 3σ noise levels both for the continuum and line data. We present two maps with robust parameters of 0.0 and 2.0 for the 1.3 mm continuum emission to emphasize different details that are present on distinct spatial scales. The continuum map with a robust parameter of 0.0 has a higher angular resolution but poor sensitivity to extended structures, while the other map with a robust parameter of 2.0 has a lower angular resolution but better sensitivity to extended structures. For the subsequent analysis, we used the map with a robust parameter of 0.0, as it was optimal for the main focus of this paper. For line imaging, the uv taper with an FWHM of 2000 kλ was applied regardless of robust parameters. We mainly present CO isotopologues and SO lines, and the maps of other lines are also shown in Appendix A. We calculated rms noise levels of the continuum map with a robust parameter of 0.0 and all the line maps from the weight information of visibility with the apparent sensitivity task. As the continuum map with a robust parameter of 2.0 exhibited stronger side lobes, we measured the rms noise level in a emission-free region for this map. All the maps were primary-beam corrected. The details of the main maps are summarized in Table 2.

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21 The scripts used for reduction can be found at https://github.com/jjtobin/edisk (Tobin 2023).
<table>
<thead>
<tr>
<th>Date</th>
<th>Antenna Configuration</th>
<th>Number of Antennas</th>
<th>Projected Baseline Length</th>
<th>Total On-source Time</th>
<th>Calibrators</th>
<th>Check Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>2021 Apr. 24</td>
<td>C-5</td>
<td>45</td>
<td>15.1 m–1.4 km</td>
<td>50 minutes</td>
<td>J1107–4449</td>
<td>J1058–8003</td>
</tr>
<tr>
<td>2021 Oct. 4</td>
<td>C-8</td>
<td>42</td>
<td>69.9 m–10.8 km</td>
<td>41 minutes</td>
<td>J0519–4546</td>
<td>J1058–8003</td>
</tr>
<tr>
<td>2021 Oct. 20</td>
<td>C-8</td>
<td>47</td>
<td>46.8 m–9.0 km</td>
<td>41 minutes</td>
<td>J0519–4546</td>
<td>J1058–8003</td>
</tr>
<tr>
<td>2021 Oct. 20</td>
<td>C-8</td>
<td>44</td>
<td>46.8 m–9.0 km</td>
<td>41 minutes</td>
<td>J1427–4206</td>
<td>J1058–8003</td>
</tr>
</tbody>
</table>
The 1.3 mm dust continuum emission maps are presented in Figure 1. Figure 1(a) shows two compact peaks that are associated with a main protostar, Ced110 IRS4A, and a fainter companion, Ced110 IRS4B, which has not been reported in previous lower-sensitivity observations. The projected distance between the two sources is $\sim 1.3''$ ($\sim 250$ au). In addition to the two compact emission sites around Ced110 IRS4A and IRS4B, an extended emission ($\sim 2''$ in radius) is detected at $\sim 5\sigma$ around $(\Delta R, \Delta \text{decl.}) = (-3'', 7.5'')$ on the northern side of the protostellar system in a wider view of the 1.3 mm continuum map, presented in Figure 1(b). An arc-like structure with a marginal detection at $3\sigma$, extending from an R.A. offset of $2.5''$ to $-2.5''$, is connected to the extended emission.

The primary emission, which is associated with Ced110 IRS4A, exhibits a flattened, disk-like shape (Figure 1(c)), and likely traces the circumstellar disk around the protostar. The peak brightness temperature of the emission is $\sim 79$ K. The peak position is measured through the Gaussian fitting to be (R.A., decl.) = (1$^\circ$06$^\prime$46$^{''}$3682, $-77^\circ$22$^{''}$32$^{''}$882). We adopt this position for the coordinates of Ced110 IRS4A and for the map center throughout this paper. The continuum emission does not show any clear substructures such as rings or gaps often found in Class II disks (e.g., Andrews et al. 2018), despite the angular resolution of $\sim 0.05''$ ($\sim 10$ au).

The secondary emission, which is associated with Ced110 IRS4B, also shows a flattened, disk-like shape (Figure 1(d)) and likely arises from the dust disk around Ced110 IRS4B, whereas it is not spatially well resolved along its minor axis. The emission around Ced110 IRS4B is less bright than the one around Ced110 IRS4A, and the peak brightness temperature is $\sim 9$ K. It exhibits three intensity peaks separated by $\sim 0.05''$ (or $\sim 9$ au) along its major axis, but the distinction of these peaks is marginal. The difference in the intensity between the three peaks and the dips between the peaks is $\sim 1-3\sigma$. The position of Ced110 IRS4B is measured through the Gaussian fitting to be (R.A., decl.) = (1$^\circ$06$^\prime$46$^{''}$7718, $-77^\circ$22$^{''}$32$^{''}$757).

We measured flux densities and dust disk radii to characterize the dust disks of Ced110 IRS4A and IRS4B. The flux densities were measured with elliptical apertures, whose semimajor axes were determined by the curve-of-growth method (Ansdell et al. 2016). In this method, we applied larger apertures until the measured flux density converged. The aperture shapes were determined based on the inclination and position angles of the dust continuum emission, which are derived in Section 4.1. The adopted final apertures and measured flux densities are summarized in Table 3. The uncertainties in the flux densities are statistical errors derived through the error propagation of the rms noise and do not include the absolute flux calibration error, which is typically 10% for ALMA Band 6 observations. The dust disk radii were also estimated with the curve-of-growth method. We adopted a definition of the dust disk radius that was used in the Lupus Class II disk survey (Ansdell et al. 2016), where the dust disk radius encloses 90% of the flux density. Following the method of the Lupus survey, uncertainties in the dust disk radii are calculated by taking the range of radii within the uncertainties of the 90% flux densities. The estimated dust disk radii of Ced110 IRS4A and IRS4B are $\sim 91.7 \pm 0.2$ au ($\sim 0''485 \pm 0''001$) and $\sim 33.6 \pm 0.6$ au ($\sim 0''178 \pm 0''003$), respectively.

Dust masses were calculated from the measured flux densities, assuming that the dust continuum emission is optically thin. We adopt the dust opacity of $2.3 \text{ cm}^2 \text{ g}^{-1}$ (Beckwith et al. 1990) with a gas-to-dust mass ratio of 100. Two different dust temperatures are adopted: a temperature of 20 K, which represents a characteristic temperature of Class II disks (Andrews & Williams 2005), and a temperature of 43 K, which is derived from an empirical scaling relation of $T_{\text{dust}} = 43 (L_{\text{bol}}/L_{\odot})^{0.25}$ representing the averaged temperature of disks embedded in envelopes (Tobin et al. 2020). Note that the peak brightness temperature of the primary emission is much higher than these averaged temperatures of disks, suggesting that an inner part of the emission is optically thick, and thus the derived mass would be a lower limit. The estimated dust masses are presented in Table 3. The uncertainties are calculated through the error propagation of the statistical errors of the flux densities. The dust mass of Ced110 IRS4A of 97.43 $M_\oplus$ at 20 K is much larger than the typical dust mass of Class II disks of $\sim 1 M_\oplus$, adopting the same temperature and a similar dust opacity (Andrews et al. 2013; Ansdell et al. 2016; Pascucci et al. 2016; Barenfeld et al. 2017; Long et al. 2018b; Ansdell et al. 2018; Ruiz-Rodriguez et al. 2018; Akesson et al. 2019; Cieza et al. 2019; Williams et al. 2019; Andrews 2020). On the other hand, it agrees with the typical dust mass of Class 0 sources of $\sim 110 M_\oplus$ under similar assumptions on the temperature and dust opacity (Tobin et al. 2020). The flux density and dust mass of Ced110 IRS4B are smaller than those of Ced110 IRS4A approximately by 2 orders of magnitude and similar to the minimum value among the Orion Class 0 sources (Tobin et al. 2020). As Ced110 IRS4B exhibits very small flux (and dust mass), we also compare its flux density with those measured in protostars with low masses or low luminosities. The flux density of Ced110 IRS4B is smaller than the typical 1.3 mm flux densities measured for disks around substellar-mass or low-mass protostellar objects ($M_\star \lesssim 0.1 M_\odot$; Lee et al. 2018; Hsieh et al. 2019; Riaz et al. 2019; Aso et al. 2023) by a factor of $\sim 5$, but is comparable to those reported for disk components of very-low-luminosity objects (1.3 $\pm$ 0.4 mJy in L1521F and 3.6 $\pm$ 1 mJy in IRAM...
In order to investigate the structures of the continuum emission in more detail, we present one-dimensional intensity profiles along their major and minor axes with the cut width corresponding to the size of one pixel (~1/10 beam size) in panels (c) and (d). Note that the color scales are in an asinh stretch in panels (a) and (b) to cover a wide dynamic range, while they are in a linear scale in panels (c) and (d). In all panels, white ellipses at the bottom left corners denote the synthesized beam size.

**Figure 1.** (a) 1.3 mm continuum emission map with a robust parameter of 0.0. The contours levels are 3, 6, 12, 24, ×σ, where σ = 0.020 mJy beam$^{-1}$. Dashed boxes show the zoom-in areas, shown in panels (c) and (d). (b) 1.3 mm continuum emission map with a robust parameter of 2.0. The contour level is 3σ, where σ = 0.018 mJy beam$^{-1}$. (c) Zoom-in view of the continuum emission associated with Ced110 IRS4A with a robust parameter of 0.0. The contour levels are the same as in panel (a). (d) Zoom-in view of the continuum emission associated with Ced110 IRS4B with a robust parameter of 0.0. The contour levels are 3, 6, 9, 12, 15, ×σ. Note that the color scales are in an asinh stretch in panels (a) and (b) to cover a wide dynamic range, while they are in a linear scale in panels (c) and (d).

**Table 3**

<table>
<thead>
<tr>
<th>Source</th>
<th>Flux Density (mJy)</th>
<th>Aperture</th>
<th>Dust Mass 20 K* (M⊕)</th>
<th>Dust Mass 43 K* (M⊕)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ced110 IRS4A</td>
<td>92.32 ± 0.04</td>
<td>1″60 × 0″38 (104°)</td>
<td>97.43 ± 0.04</td>
<td>38.85 ± 0.02</td>
</tr>
<tr>
<td>Ced110 IRS4B</td>
<td>1.96 ± 0.01</td>
<td>0″31 × 0″09 (85°)</td>
<td>2.07 ± 0.01</td>
<td>0.825 ± 0.004</td>
</tr>
</tbody>
</table>

Note. * Assumed temperature.
Figures 2 and 3. The position angles of 104° and 85° were adopted for the primary and secondary continuum emission, respectively, which were derived through the fitting of intensity distribution models in Section 4.1. The intensity profile along the major axis for Ced110 IRS4A, presented in Figure 2(a), interestingly, shows bumpy plateaus at a radius of ∼0′′2–0′′4, where the intensity distributions are close to flat. It also shows an asymmetry across a radial range of 0′′05–0′′74, where the emission on the eastern side of the protostar is brighter than on the western side by ∼6σ on average. An asymmetry is also clearly seen along the minor axis in Figure 2(b), where the emission on the southern side is significantly stronger than on the northern side. The intensity profiles for the continuum emission of Ced110 IRS4B are presented in Figure 3. The intensity profile along the continuum major axis for Ced110 IRS4B shows three intensity peaks, although these structures are not significant considering the rms noise level, shown as a shaded region. The shape of the intensity profile along the minor axis is not well resolved.

3.2. Lines

Moment maps of the C^{18}O, 13CO, ^{12}CO J = 2−1, and SO J_N = 6−5 lines are presented in Figures 4–7. Moment maps of other lines are shown in Appendix A. The moment zero and one maps are calculated by integrating the emission detected above 3σ.

The C^{18}O emission is detected around Ced110 IRS4A, as shown in Figure 4(a). The emission exhibits a flattened shape with a size comparable to that of the continuum emission and an apparent deficit of emission at the protostellar position. The deficit of emission at the center is caused because the cold, foreground line emission absorbs the continuum emission around the line center and thus the continuum is over-subtracted. Indeed, in the velocity channel maps shown in Figure A1, negative emission is clearly seen at the position of Ced110 IRS4A at 3.85−4.52 km s^{−1}, where most of the C^{18}O emission is resolved. In the moment one map presented in Figure 4(b), a clear velocity gradient is seen along the direction of the continuum elongation across the protostar, suggesting a rotational motion of its disk and/or an envelope. The C^{18}O emission is also detected around Ced110 IRS4B at ≥3σ. Figures 4(c) and (d) show wider views of the moment zero and one maps, respectively. An extended emission at the northern side of the protostar and an arc-like structure connected to the extended component are observed at 5σ in the ^{13}CO emission. These structures are very similar to the north-extended and arc-like structures of the 1.3 mm continuum emission. The extended ^{13}CO emission on the northern side has a similar extent to that of the continuum emission (∼2″ in semimajor axis). The arc-like structure is more clearly seen in the C^{18}O emission over a velocity range of 4.85−5.86 km s^{−1} (see also Figure A4), and appears to be one-fourth of a circle from east to north. A clear velocity gradient is seen along the arc-like structure and the northern extended component.

The ^{12}CO emission is detected around Ced110 IRS4A as well as the C^{18}O emission, as seen in the moment zero and one maps in Figures 5(a) and (b). The overall features of the ^{13}CO emission associated with Ced110 IRS4A are similar to those of the C^{18}O emission: the ^{12}CO emission shows an elongated shape and a velocity gradient in a direction similar to the direction of the continuum elongation, suggesting rotation of a disk and/or an envelope. The moment zero map of the ^{13}CO emission also exhibits an apparent deficit of emission at the central, which is likely due to the continuum oversubtraction with the cold, foreground line emission around the line center (see Figure A2). In addition to these structures, the ^{13}CO emission exhibits four peaks at the edge of the continuum.
emission of Ced110 IRS4A, making a dark lane along the continuum major axis at radii of 0.1–0.5. These features are not seen in the C$^{18}$O emission. The four peaks are slightly asymmetric and the emission on the northern side is brighter. These features suggest that the 13CO emission around the Ced110 IRS4A originates mainly from the disk surface. This point is discussed in more detail in Section 5.1.2. The 13CO emission is also seen around Ced110 IRS4B, but it is much more extended than the continuum emission and connected to Ced110 IRS4A. Figures 5(c) and (d) show wider views of the moment zero and one maps of the 13CO emission. The extended structures of the 13CO emission are more complex than those of the C$^{18}$O emission. The 13CO emission does not show a component corresponding to the arc-like structure found in the C$^{18}$O and continuum emission. This could be because the arc-like structure is mostly obscured by optically thick, extended foreground gas in the 13CO emission, as the emission at the velocity range of 3.85–5.52 km s$^{-1}$ is resolved in the velocity channel maps in Figure A5. The 13CO emission shows the arc-like structure only at a velocity of 5.86 km s$^{-1}$ in the velocity channel maps.

The 12CO emission shows four intensity peaks around Ced110 IRS4A and a dark lane along the continuum major axis, as the 13CO emission does, but more clearly in Figure 6(a). The two intensity peaks on the northern side of the continuum emission are brighter than those on the southern side. In Figure 6(b), a clear velocity gradient appears along the continuum elongation around Ced110 IRS4A, as was seen in the C$^{18}$O and 13CO emission. The 12CO emission is also extended around Ced110 IRS4B. On larger scales, as presented

Figure 4. Moment zero and one maps of the C$^{18}$O $J = 2$–$1$ emission (color) overlaid with the 1.3 mm continuum maps (contours). Panels (a) and (c) show zoom-in and wide views of the moment zero map, and panels (b) and (d) show zoom-in and wide views of the moment one map, respectively. The 1.3 mm continuum maps with robust parameters of 0.0 and 2.0 are overlaid on the zoom-in and wide views of the moment maps, respectively. The contour levels are the same as those of Figure 1(a) and (b). The filled and opened ellipses at the bottom left corners represent the synthesized beam sizes of the C$^{18}$O and continuum maps, respectively.
in Figures 6(c) and (d), the $^{12}$CO emission is extended from east to west around Ced110 IRS4A with a clear velocity gradient. The $^{12}$CO emission is resolved over a velocity range of 3.50–5.41 km s$^{-1}$ (see Figure A6), and thus does not show any structures corresponding to the arc-like structures found in the continuum and C$^{18}$O emission. No clear outflow from Ced110 IRS4A and IRS4B is seen in the $^{12}$CO emission, though $^{12}$CO emission is a typical tracer of outflows around protostars.

The SO emission is not detected around Ced110 IRS4A or IRS4B, but it shows an arc-like structure with a velocity gradient along the structure in Figure 7, as in the case of the C$^{18}$O and continuum emission. The SO arc-like structure appears within the same velocity range of 4.85–5.86 km s$^{-1}$ as that of the C$^{18}$O emission. The SO emission also exhibits a blueshifted component at a distance of $\sim 6''$ ($\sim 1000$ au) on the southern side of the Ced110 IRS4 system.

4. Analysis

4.1. Intensity Distribution Model

4.1.1. Ced110 IRS4A

The continuum emission associated with Ced110 IRS4A exhibits bumps along its major axis, suggesting a shallow, ring-like structure in the intensity distribution. In order to investigate these structures in more detail, we performed fitting of two-dimensional intensity models.

We construct two types of intensity distributions: a smooth intensity distribution and an intensity distribution with a ring component at a certain radius. The smooth intensity distribution consists of a point source, a compact Gaussian, and a broad Gaussian, while the intensity distribution with a ring component is modeled with a point source, a compact Gaussian, and an azimuthally symmetric Gaussian ring, which is expressed by...
the following equation:

\[ I_r(r) = a_r \exp \left\{ -\frac{(r - r_0)^2}{2\sigma_r^2} \right\}, \]  

where \( r \) is the radius deprojected by the inclination angle \( i_r \) and the position angle \( pa_r \), \( a_r \) is the peak intensity of the ring component, \( r_0 \) is the ring location in radius, and \( \sigma_r \) is the ring width. A point source is included in both models to reproduce the observed high brightness temperature at the peak position, which cannot be reproduced by a compact Gaussian component only. The intensity models are compared to the observations after beam convolution. We fitted these two models to the observed continuum map with the Markov Chain Monte Carlo (MCMC) code emcee (Foreman-Mackey et al. 2013). We performed the fitting in the image plane rather than in the u-v plane for simplicity, as Ced110 IRS4B is contained in the same field of view. All model parameters and their best-fit values are summarized in Table 4.

The best-fit model images and residual images for the two models are presented in Figures 8(a) and (b), and in Figures 9(a) and (b). Both the smooth and ring models show large residuals on the southern side of the protostar along the continuum minor axis. This is because the intensity models are constructed to be axisymmetric, while the observed continuum emission is asymmetric along the minor axis. The smooth model exhibits significant residuals \( \geq 6\sigma \) and \( \leq -6\sigma \) along the continuum major axis, while the ring model shows fewer residuals. The one-dimensional intensity and residual profiles along the major axis are presented in Figures 8(c) and 9(c) to show this feature more clearly. The residual profile of the smooth model in Figure 8(c) shows large, systemic residuals \( \geq 6\sigma \) and \( \leq -6\sigma \) around offsets of \(-0.3^\prime\) and \(0.3^\prime\). On the other hand, residuals for the ring model along the major axis are...
Figure 7. (a) Moment zero and (b) one maps of the SO emission (color) overlaid with the 1.3 mm continuum maps with a robust parameter of 2.0 (contours). The contour levels are as the same as those of Figure 1(b). The filled and opened ellipses at the bottom left corners represent the synthesized beam sizes of the SO and continuum maps, respectively.

Table 4
Parameters of the Intensity Distribution Models

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Description</th>
<th>Best-fit Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_0 )</td>
<td>mJy</td>
<td>Flux density of the point source</td>
<td>0.66 ± 0.01</td>
</tr>
<tr>
<td>( a_0 \times 10^{-3} ) mJy pixel (^{-1} )</td>
<td></td>
<td>Amplitude of the first Gaussian</td>
<td>21.79 ± 0.11</td>
</tr>
<tr>
<td>( x_0 )</td>
<td>mas</td>
<td>R.A. offset coordinate of the center of the first Gaussian and of the point source</td>
<td>-2.03 ± 0.05</td>
</tr>
<tr>
<td>( y_0 )</td>
<td>mas</td>
<td>Decl. offset coordinate of the center of the first Gaussian and of the point source</td>
<td>-0.60 ± 0.09</td>
</tr>
<tr>
<td>( \sigma_{\text{maj},0} )</td>
<td>mas</td>
<td>Width (standard deviation) of the first Gaussian along the major axis</td>
<td>51.80 ± 0.14</td>
</tr>
<tr>
<td>( \sigma_{\text{min},0} )</td>
<td>mas</td>
<td>Width (standard deviation) of the first Gaussian along the minor axis</td>
<td>17.72 ± 0.09</td>
</tr>
<tr>
<td>( \rho_{\text{a}0} )</td>
<td>°</td>
<td>Position angle of the first Gaussian</td>
<td>105.06 ± 0.08</td>
</tr>
<tr>
<td>( a_1 \times 10^{-3} ) mJy pixel (^{-1} )</td>
<td></td>
<td>Amplitude of the second Gaussian</td>
<td>27.43 ± 0.09</td>
</tr>
<tr>
<td>( x_1 )</td>
<td>mas</td>
<td>R.A. offset coordinate of the center of the second Gaussian</td>
<td>-0.05 ± 0.04</td>
</tr>
<tr>
<td>( y_1 )</td>
<td>mas</td>
<td>Decl. offset coordinate of the center of the second Gaussian</td>
<td>1.41 ± 0.08</td>
</tr>
<tr>
<td>( \sigma_{\text{maj},1} )</td>
<td>mas</td>
<td>Width (standard deviation) of the second Gaussian along the major axis</td>
<td>65.98 ± 0.20</td>
</tr>
<tr>
<td>( \sigma_{\text{min},1} )</td>
<td>mas</td>
<td>Width (standard deviation) of the second Gaussian along the minor axis</td>
<td>19.61 ± 0.07</td>
</tr>
<tr>
<td>( \rho_{\text{a}1} )</td>
<td>°</td>
<td>Position angle of the second Gaussian</td>
<td>104.44 ± 0.05</td>
</tr>
<tr>
<td>( a_r \times 10^{-3} ) mJy pixel (^{-1} )</td>
<td></td>
<td>Amplitude of the Gaussian ring</td>
<td>5.23 ± 0.01</td>
</tr>
<tr>
<td>( x_r )</td>
<td>mas</td>
<td>R.A. offset coordinate of the center of the Gaussian ring</td>
<td>4.89 ± 0.23</td>
</tr>
<tr>
<td>( y_r )</td>
<td>mas</td>
<td>Decl. offset coordinate of the center of the Gaussian ring</td>
<td>-6.77 ± 0.08</td>
</tr>
<tr>
<td>( r_r )</td>
<td>mas</td>
<td>Radius of the Gaussian ring</td>
<td>215.77 ± 1.03</td>
</tr>
<tr>
<td>( \sigma_r )</td>
<td>mas</td>
<td>Width (standard deviation) of the Gaussian ring</td>
<td>132.05 ± 0.58</td>
</tr>
<tr>
<td>( i_r )</td>
<td>°</td>
<td>Inclination angle of the Gaussian ring</td>
<td>76.31 ± 0.02</td>
</tr>
<tr>
<td>( \rho_{\text{a}r} )</td>
<td>°</td>
<td>Position angle of the Gaussian ring</td>
<td>103.72 ± 0.02</td>
</tr>
</tbody>
</table>

Note.

\( ^a \) \( k \) is the number of free parameters, and BIC is the Bayesian information criterion calculated with the best-fit parameters.
mostly less than $3\sigma$. Slightly large residuals of $4\sigma$ on average, with a maximum residual of $8\sigma$, are seen at offsets of $\sim -0^\prime 4$ to $\sim -0^\prime 05$. These residuals are comparable to the significance level of the asymmetry of the observed continuum emission along the major axis ($\sim 6\sigma$ on average) found within the same radial range in Figure 2(a). Therefore, the slightly large differences between the observations and the ring model at these offsets are due to the asymmetric structure of the observed continuum emission, which is not taken into account in the intensity models.

In order to evaluate which model better describes the observed map quantitatively taking the difference in the number of free parameters into account, we calculate the Bayesian information criterion (BIC), which is defined as follows, for each model:

$$
\text{BIC} = k \ln(n) - 2 \ln(\hat{L}),
$$

where $k$ is the number of free parameters, $n$ is the number of data points, and $\hat{L}$ is the maximum likelihood. The logarithm of the likelihood is defined as follows:

$$
\ln[L(\Theta)] = -\frac{1}{2} \sum_{i=1}^{n} \left( \frac{(I_{\text{obs},i} - I_{\text{model},i})^2}{\sigma^2} \right) + \ln(2\pi\sigma^2),
$$

where $I_{\text{obs}}$ is the observed intensity, $I_{\text{model}}$ is the model intensity with a parameter set $\Theta$, and $\sigma$ is the rms noise of the continuum map. The logarithm of the maximum likelihood ($\ln(\hat{L})$) is, thus, derived from Equation (3) and the best-fit parameters of $\Theta$. The BIC for the smooth model and the ring model are calculated to be $-43,800$ and $-51,500$, respectively, where a difference between BIC values larger than 10 indicates a very strong evidence in favor of the model with the lower BIC value (Kass & Raftery 1995). Hence, we conclude that an intensity distribution with a ring component better explains the observed dust continuum emission. We have also tested intensity distributions with a power-law profile, which is often used to describe dust continuum emission from disks, and obtained
similar results that include a ring component and better explain the observations, as presented in Appendix B. We adopt a position angle of 104° and an inclination angle of 76° of the ring model as those of the dust disk around Ced110 IRS4A. Note that the inclination angle is a lower limit, as the assumption of a geometrically thin disk may not be valid. Combining the fitting results of the ring model for Ced110 IRS4A, the separation between the centers of Ced110 IRS4A and IRS4B on the plane of the sky, and the position angle of the center of Ced110 IRS4B relative to that of IRS4A are calculated to be 1°3291 ± 0°0003 (or 251.21 ± 0.06 au) and 84°54 ± 0°03, respectively.

4.2. Rotation Curve

Rotational motions are clearly seen in CO isotopologue lines around Ced110 IRS4A. These lines are also detected around Ced110 IRS4B, although they do not show clear velocity gradients around the protostar in the moment one maps. In this subsection, the rotational motion around the protostars is investigated in more detail using the C18O and 13CO lines, which are less affected by the absorption by the foreground cloud and imaged with velocity resolutions of a factor of 4 higher than that of the 13CO line.

4.2.1. Ced110 IRS4A

Position–velocity (PV) diagrams of the C18O and 13CO emission along the continuum major axis of Ced110 IRS4A are presented in Figure 11. The C18O PV diagram clearly exhibits a feature of differential rotation, where velocity increases with decreasing radius. On the other hand, it shows no clear feature of symmetric infall, where both the blueshifted and redshifted velocity components appear at the same offset. These features
measurements of velocities at a given offset; blue and cyan markers indicate measurements at blueshifted velocity; and red and pink markers indicate measurements at redshifted velocity. The solid and dashed curves show the power-law functions representing the best fits to the ridges and edges, respectively. The vertical and horizontal bars in the bottom left corners represent the FWHM of the synthesized beam and the velocity resolution, respectively.

Figure 11. Position–velocity diagrams of (a) C$^{18}$O and (b) $^{13}$CO emission of Ced110 IRS4A cut along its continuum major axis. The contour levels are from 3σ to 12σ in steps of 3σ. The dashed contours represent negative intensities. The round and triangle markers denote the determined ridges and edges, respectively. The color of the marker indicates the properties of the data points: blue and red markers show measurements of positions at a given velocity; cyan and pink markers show measurements of velocities at a given offset; blue and cyan markers indicate measurements at blueshifted velocity; and red and pink markers indicate measurements at redshifted velocity. The solid and dashed curves show the power-law functions representing the best fits to the ridges and edges, respectively. The vertical and horizontal bars in the bottom left corners represent the FWHM of the synthesized beam and the velocity resolution, respectively.

Table 6
Results of the Rotation Curve Fitting

<table>
<thead>
<tr>
<th>Line</th>
<th>Velocity Range</th>
<th>Ridge/Edge</th>
<th>$V_0$ (km s$^{-1}$)</th>
<th>$R_0$ (au)</th>
<th>$p$</th>
<th>$V_{\text{sys}}$ (km s$^{-1}$)</th>
<th>$M_*$ ($M_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$^{18}$O</td>
<td>Whole</td>
<td>Ridge</td>
<td>3.59</td>
<td>78.6 ± 0.7</td>
<td>0.531 ± 0.019</td>
<td>4.64 ± 0.01</td>
<td>1.21 ± 0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Edge</td>
<td>3.63</td>
<td>92.0 ± 1.3</td>
<td>0.669 ± 0.070</td>
<td>4.70 ± 0.03</td>
<td>1.45 ± 0.02</td>
</tr>
<tr>
<td>$^{13}$CO</td>
<td>Whole</td>
<td>Ridge</td>
<td>3.20</td>
<td>80.6 ± 0.5</td>
<td>0.761 ± 0.009</td>
<td>4.55 ± 0.01</td>
<td>0.99 ± 0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Edge</td>
<td>3.10</td>
<td>110.4 ± 1.0</td>
<td>0.876 ± 0.026</td>
<td>4.59 ± 0.02</td>
<td>1.27 ± 0.01</td>
</tr>
<tr>
<td>$^{13}$CO</td>
<td>$V_{\text{rot}} \geq 3$ km s$^{-1}$</td>
<td>Ridge</td>
<td>4.16</td>
<td>57.3 ± 0.8</td>
<td>0.596 ± 0.030</td>
<td>4.61 ± 0.03</td>
<td>1.19 ± 0.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Edge</td>
<td>4.16</td>
<td>75.3 ± 1.3</td>
<td>0.518 ± 0.024</td>
<td>4.59 ± 0.02</td>
<td>1.56 ± 0.03</td>
</tr>
</tbody>
</table>

Note. Column 1: Line used for the fitting. Column 2: Velocity range of the data used for the rotation curve fitting. Column 3: Definition of the representative points used for the fitting. Columns 4–7: Parameters in Equation (4). $V_0$ is the mean velocity of the data points, and the other three parameters are free parameters in the fitting. Column 8: Dynamical mass estimated from the mean velocity $V_0$ assuming Keplerian rotation and an inclination angle of 76°.

We use these two different definitions to discuss the lower and upper limits of the dynamical mass based on Keplerian rotation (Maret et al. 2020). Then, we fit the following power-law function to the obtained data points to examine the radial dependence of the differential rotation:

$$V_{\text{rot}} = |V_{\text{LSR}} - V_{\text{sys}}| = V_0 \left( \frac{R}{R_0} \right)^{-p},$$

where $V_{\text{rot}}$ is the rotational velocity, $V_{\text{LSR}}$ is the local standard of rest (LSR) velocity of the obtained data points, and $V_{\text{sys}}$ is the systemic velocity. We fix $V_0$ at the mean velocity of the data points, and set the remaining three parameters ($R_0$, $p$, $V_{\text{sys}}$) as free parameters in the fits.

The results from the fits are summarized in Table 6. The best-fit power-law indices for the edges and ridges for the C$^{18}$O emission are 0.669 ± 0.070 and 0.531 ± 0.019, respectively, which agree with Keplerian rotation ($V_{\text{rot}} \propto R^{-0.5}$) within fitting uncertainties of 2–3σ. The fitting to the $^{13}$CO emission, on the other hand, results in power-law indices of 0.761 ± 0.009 and 0.875 ± 0.026, which are larger than that for a Keplerian disk. This difference in the slopes obtained from the C$^{18}$O and $^{13}$CO imply that the differential motion traces the Keplerian rotation of a disk rather than rotation of an infalling envelope. The $^{13}$CO PV diagram shows a similar feature of differential rotation, while it also exhibits faint blueshifted and redshifted emission on the west and east sides, respectively, which is not expected for a pure rotational motion.

To test whether the observed rotational motions originate from a Keplerian disk, we fit a power-law function to the spin-up feature using the pvanalysis tool of the Spectral Line Analysis/Modeling (SLAM; Aso & Sai 2023)22 code and examine its radial dependence. The detail of the fitting method can be found in Ohashi et al. (2023). Here, we only briefly describe the fitting method. First, the representative ridge (e.g., Yen et al. 2013) and edge (e.g., Seifried et al. 2016) positions (or velocities) are derived from a one-dimensional cut of the PV diagram along the position (or velocity) axis. The ridge is defined as the intensity-weighted mean calculated using emission above a given threshold, while the edge is defined as the outermost contour with a given threshold, where a threshold of 6σ is adopted to exclude noise in the analysis here.

22 https://github.com/jinshisai/SLAM
emission is likely due to the different velocity ranges of the fitted data points. The data points obtained from the C18O emission trace relatively high-velocity components of $V_{\text{rot}} \gtrsim 3$ km s$^{-1}$, while those for the 13CO emission include lower-velocity components of $\sim 1.5$ km s$^{-1}$. The lower-velocity components of the 13CO emission could trace a rotational motion of the infalling envelope ($V_{\text{rot}} \propto r^{-1}$; e.g., Yen et al. 2013) rather than the rotation of a disk. Moreover, the 13CO emission would be more affected by the optical depth and spatial filtering effects at lower velocities. We performed the fitting with high-velocity components of the 13CO emission within a velocity range similar to that for the C18O emission ($V_{\text{rot}} \gtrsim 3$ km s$^{-1}$, corresponding to radii of $\lesssim 120$ au) and obtained power-law indices of $0.518 \pm 0.024$ and $0.596 \pm 0.030$, which well agree with Keplerian rotation. Hence, the inner region within a radius of $\sim 120$ au is likely part of a Keplerian disk.

The protostellar mass is estimated from the rotational motion measured with the ridges and edges for the C18O emission to be $\sim 1.21$ and $\sim 1.45 M_\odot$, respectively, assuming an inclination angle of 76°. The dynamical mass estimated using ridges and edges assuming Keplerian rotation tends to be underestimated and overestimated, respectively (Maret et al. 2020). Therefore, our analysis suggests that the protostellar mass of Ced110 IRS4 is within a range of $\sim 1.21$–$1.45 M_\odot$. The systemic velocity of Ced110 IRS4A is measured to be $2.69 \pm 0.26$ km s$^{-1}$ as the systemic velocity of Ced110 IRS4B with an uncertainty derived through the error propagation of the fitting errors.

4.2.2. Ced110 IRS4B

Figure 12 shows PV diagrams of the C18O and 13CO emission cut along the continuum major axis of Ced110 IRS4B. To study gas motions relative to the protostellar system, we measure the systemic velocity of Ced110 IRS4B from the spectra of the two lines measured at the protostellar position, presented in Figure 13. Both lines exhibit Gaussian-shaped spectra, although the 13CO spectrum would be affected by absorption by the resolved foreground gas at a velocity of $\sim 3.9$ km s$^{-1}$ (see also Figure A2). The Gaussian fitting to the C18O and 13CO spectra results in central velocities of $2.79 \pm 0.26$ km s$^{-1}$ and $2.59 \pm 0.05$ km s$^{-1}$, respectively. Thus, we adopted a mean value of $2.69 \pm 0.26$ km s$^{-1}$ as the systemic velocity of Ced110 IRS4B with an uncertainty derived through the error propagation of the fitting errors. In Figure 12(a), the C18O emission appears around the protostar across LSR velocities of $\sim 1.5$–$4.0$ km s$^{-1}$, although the emission is detected only at $3\sigma$. The 13CO emission shows a marginal feature of a differential motion on the east side of the protostar: the velocity slightly increases with decreasing radius at offsets of $-1''$–$0''$ at the blueshifted velocity. Such a feature of the differential rotation is less clear on the west side of the protostar. This could be because the relatively high-velocity components ($\sim 3.5$ km s$^{-1}$) are obscured by the optically thick foreground gas, which is resolved in our map (see Figure A2). Strong C18O and 13CO emission found around an offset of $1''$ is associated with Ced110 IRS4A, as it is located along the PV cut direction.

![Figure 12](image-url)

**Figure 12.** Position–velocity diagrams of (a) C18O and (b) 13CO emission of Ced110 IRS4B cut along its continuum major axis. The contour levels are from $3\sigma$ to $12\sigma$ in steps of $3\sigma$. The dashed contours represent negative intensities. The solid and dashed curves correspond to Keplerian rotation with a central mass of 0.02 and 0.05 $M_\odot$, respectively, without correction of the inclination angle. The vertical and horizontal bars in the bottom left corners represent the FWHM of the synthesized beam and the velocity resolution, respectively.

![Figure 13](image-url)

**Figure 13.** Spectra of the C18O and 13CO $J = 2$–$1$ lines measured within a radius of $0''15$ around Ced110 IRS4B. The curves show the best-fit Gaussian functions.
While it is difficult to apply the same analysis as that for Ced110 IRS4A because of the less clear feature of the rotational motion, we overlay curves of Keplerian rotation to make a rough estimate of the mass of Ced110 IRS4B assuming that the emission is associated with a Keplerian disk. The Keplerian curves with stellar masses of 0.02 and 0.05 $M_\odot$ without correction of the inclination angle appear to agree with the intensity peaks and the outermost contours of the emission, respectively. A correction of the inclination angle of $\sim 73^\circ$ increases the above mass estimate by 5%. However, we note that the inclination angle of the disk of Ced110 IRS4B is quite uncertain, as the continuum emission is not well resolved along its minor axis.

5. Discussion

5.1. Structures and Orientation of the Disk of Ced110 IRS4A

The rotation curves derived in Section 4.2 suggest that the inner region within a radius of $\sim 120$ au around Ced110 IRS4A is part of a Keplerian disk. Thus, the dust continuum emission of Ced110 IRS4A with a radius of $\sim 91.7$ au would also originate from a disk rather than a surrounding envelope. In the following subsections, we discuss the structures of the dust disk of Ced110 IRS4A based on the observed dust continuum structures and the orientation of the disk.

5.1.1. Possible Annular Substructure

One of the main focuses of this paper is to investigate whether the disk(s) exhibit substructures or not, which might tell us when planet formation begins. The dust continuum emission of Ced110 IRS4A does not show any clear gaps or rings, which are commonly reported in Class II disks (e.g., Andrews et al. 2018). Interestingly, however, the continuum emission shows shallow bumps along its major axis, which can be interpreted as a shallow, ring-like structure at a radius of $\sim 40$ au. This might indicate an early formation of an annular substructure in the dust disk. On the other hand, the continuum emission could be optically thick, as it shows a relatively high peak brightness temperature of 79 K, and thus the dust continuum emission might not exactly trace the actual surface density of the disk (e.g., Ricci et al. 2018). In such a case, a nonmonotonic temperature profile in the disk could be contributing to the shallow, ring-like structure of the dust continuum emission (Cleev 2016; Facchini et al. 2017). The high inclination angle of the disk could also cause the cold disk midplane to obscure some of the emission from the disk itself, which may produce apparent inflections in the intensity profile, when the disk is not geometrically thin.

We can roughly estimate the optical thickness of the continuum emission at the bump radius ($\sim 0.82$ or $\sim 40$ au) by comparing the dust brightness temperature to a typical disk temperature model. The observed brightness temperature is equal to the disk temperature when the dust emission is optically thick. The radial profile of the midplane temperature can be expressed as follows, assuming a passively heated, flared disk (Chiang & Goldreich 1997; D’Alessio et al. 1998; Dullemoud et al. 2001):

$$T_{\text{mid}}(r) = \left( \frac{\varphi L_\ast}{8\pi r^2 \sigma_{\text{SB}}} \right)^{0.25},$$  

where $r$ is the radius, $L_\ast$ is the stellar luminosity, $\sigma_{\text{SB}}$ is the Stefan–Boltzmann constant, and $\varphi$ is the disk flaring angle in radians. Although the flaring angle is uncertain, a flaring angle of 0.02 ($\sim 1^\circ$) is often adopted for Class II disks as a conservative assumption (Huang et al. 2018). This flaring angle yields a pressure scale height of $\sim 7$ au at a radius of 100 au, assuming that the ratio of the photosphere height to the pressure scale height is about 2.5, as suggested by a simulation work (Baillié & Charnoz 2014). This is roughly consistent with a gas pressure scale height of $\sim 6$ au at a radius of 100 au derived from the measured protostellar mass and a temperature calculated for a flaring angle of 0.02. Hence, the adopted flaring angle would be reasonable. Assuming $\varphi = 0.02$ and $L_\ast = L_{\text{bol}}/1 = 1 L_\odot$, the disk temperature is estimated to be about 20 K at the radius of 40 au, which is comparable to the observed brightness temperature of $\sim 20$ K at 40 au derived with the full Planck function. The resultant temperature varies only by 20%–30% when the flaring angle and the stellar luminosity changes by a factor of a few. Hence, we could not rule out the possibility that the continuum emission is optically thick around the shoulder radius even considering uncertainties of the assumed parameters by a factor of a few. We note that this is a very rough estimate based on a simple model of the temperature distribution. van’t Hoff et al. (2020) suggest that young, embedded disks could be warmer than Class II disks. A protostellar disk model of Harsono et al. (2015), where a total luminosity of the central source is $\sim 1 L_\odot$ and an envelope mass of 1 $M_\odot$, predicts a temperature $\sim 40$ K at a radius of 40 au. The infalling envelope may also keep embedded disks warmer (Whitney et al. 2003; Tobin et al. 2020). Observations at longer wavelengths, where optically thinner emission is expected, and/or the radiative transfer modeling are required to reveal the details and origin of the ring-like structure of the 1.3 mm continuum emission.

5.1.2. Asymmetry and Orientation of the Disk

The dust continuum emission shows asymmetry along both its major and minor axes. The asymmetry along the minor axis is also seen in several protostellar systems of the eDisk sample (Ohashi et al. 2023). These structures can be explained by a geometric effect, which is a combination of the optical depth effect and disk flaring. When the dust continuum emission of an inclined disk is optically thick, we look at a cold disk edge on one side of the plane of the sky but look at a warm disk surface on the other side along the minor axis (e.g., Villenave et al. 2020, Lin et al. 2023). If this is the case for Ced110 IRS4A, the southern side (brighter side) corresponds to the disk surface facing the observer. However, as the CO and $^{13}$CO emission suggests an opposite disk orientation, this would not be the case for Ced110 IRS4A and the asymmetry of the continuum emission along the minor axis seems to be associated with the temperature or surface-density structure of the disk. The CO and $^{13}$CO emission exhibit asymmetric intensity peaks in the northern and southern parts with respect to the dark lane along the major axis of the continuum emission and likely arises from layers above the disk midplane. Such optically thick lines arising from the disk surface can tell the disk orientation with respect to the plane of the sky; the emitting layer in front of the disk midplane, as viewed from the observer, appears brighter than that behind the disk midplane (Rosenfeld et al. 2013; Pinte et al. 2018). The CO and $^{13}$CO
emission of Ced110 IRS4A show stronger intensity peaks on the northern side, suggesting that the northern side corresponds to the disk surface facing the observer. This is opposite to what is inferred from the continuum emission when assuming an optically thick and flared dust disk. Hence, if we assume that the orientations of the gas and dust disks indeed are consistent, the implication is that the dust disk is not significantly flared. Also, as the continuum emission shows a clear asymmetry along the major axis, the ring-like structure could be asymmetric in the azimuthal direction and thus result in an asymmetry along the minor axis. The ring-like structure is not resolved along the minor axis because of the limited spatial resolution and its high optical depth at the center. Observations at higher angular resolution or longer wavelengths would reveal the asymmetry of the ring-like structure in more detail.

Note that previous studies suggest that an outflow is tilted to the near and far sides against the observer on the southern and northern sides of the protostar, respectively, on large scales of \( \sim 1000–10,000 \) au (Zinnecker et al. 1999; Pontoppidan & Dullemond 2005; Hiramatsu et al. 2007), which is opposite to the tilt of the disk normal inferred from the CO and \(^{13}\)CO emission. However, the large-scale outflow, which should be ejected in past, would not necessarily be aligned orthogonal to the disk in the current epoch. A small tilt of \( \sim 15^\circ \) can change the near and far sides of the outflow against the observer, as the disk is close to edge-on \((i \sim 76^\circ)\). As outflows typically have opening angles of \( \geq 20^\circ \) (Arce & Sargent 2006; Velusamy et al. 2014), part of the outflow cavity of Ced110 IRS4A comes to the near and far sides against the observer on the southern and northern sides of the protostar, respectively, even when the axis of the large-scale outflow is aligned with the current disk normal. Therefore, if one side of the outflow cavity is enhanced by interaction with an inhomogeneous envelope, it may cause the outflow orientation to appear opposite to that expected from the disk orientation. Our CO map does not show any clear bipolar outflow on smaller scales of \( \sim 100–1000 \) au (see Figure A6). This could be because the outflow has a small projected velocity due to the large inclination angle of the disk \((\text{i.e., outflow axis nearly parallel to the plane of the sky})\), and thus is obscured by the extended, optically thick foreground gas. Observations of the outflow on scales of \( \lesssim 1000 \) au would help to put a stronger constraint on the disk orientation.

5.2. Extended Arc-like Structure

The SO and \(^{18}\)O emission show arc-like structures on the northern side of the protostellar system at a radius of \( \sim 1100 \) au \((\sim 6')\). A similar structure is also seen in the other lines, \(^2\)H\(_2\)CO and c-C\(_2\)H\(_2\) of our data (see Appendix A) and at near-infrared wavelengths (Pontoppidan & Dullemond 2005). A possible interpretation of this structure is a shocked shell caused by an outflow, as the SO line is often considered as a shock tracer (Bachiller & Pérez Gutiérrez 1997; Wakelam et al. 2005). The arc-like structure is seen at LSR velocities of 4.69–6.02 km s\(^{-1}\) (see Figure A4 and A7), which are redshifted with respect to the systemic velocity of 4.67 km s\(^{-1}\). This is opposite to the disk orientation inferred from the CO emission but consistent with the orientation of the reflection nebula and the large-scale outflow on scales of \( \gtrsim 1000 \) au (Zinnecker et al. 1999; Pontoppidan & Dullemond 2005; Hiramatsu et al. 2007). Thus, the arc-like structure could be formed by the large-scale outflow ejected in the past. The LSR velocities of the arc-like structure correspond to velocities of about 0–1.3 km s\(^{-1}\) relative to the systemic velocity. The highest velocity of the arc-like structure is comparable to the escape velocity of 1.37–1.50 km s\(^{-1}\) at a radius of \( \sim 1130 \) au, assuming a protostellar mass of \( 1.21–1.45 \) M\(_\odot\). Although the inclination angle of the arc-like structure is uncertain as it is not necessarily aligned with the disk normal, the inclination angle of the system is estimated to be \( 70^\circ \pm 5^\circ \) to explain the color gradient of the reflection nebula (Pontoppidan & Dullemond 2005). Assuming \( i = 70^\circ \), the deprojected velocity of the arc-like structure can be up to \( \sim 3.8 \) km s\(^{-1}\) with respect to the systemic velocity and much higher than the escape velocity. Thus, this structure could be moving outward to escape from the system.

An infalling flow could be another possible origin of the arc-like structure, as nonaxisymmetric, infalling flows are reported in a couple of protostellar systems \((\text{e.g.,} \text{Yen et al. 2014, 2019; Garufi et al. 2022; Thieme et al. 2022})\). However, the trajectory of the arc-like structure is not connected to the disks associated with either Ced110 IRS4A or IRS4B. Moreover, the largest velocity of the arc-like structure is close to the escape velocity. Considering that the trajectory of the arc-like structure is not quite along the line of sight, the observed velocity would be too high for the arc-like structure to be accreted onto the protostellar system. The arc-like structure could also be a part of a filamentary structure of the foreground cloud. However, previous single-dish observations of the parental cloud in N\(_2\)H\(^+\) show that it has an LSR velocity of around 4.3 km s\(^{-1}\), which is smaller than the highest velocity of the arc-like structure by 1.7 km s\(^{-1}\). Hence, the arc-like structure would not likely be a part of a filamentary structure in the foreground cloud.

5.3. Binary System

The binary system consisting of Ced110 IRS4A and IRS4B with a projected separation of \( \sim 250 \) au is spatially resolved from the current observations. The properties of the two protostars are summarized in Table 7. The stellar mass ratio \( q = M_2/M_1 \), where \( M_1 \) and \( M_2 \) are the primary and secondary stellar masses, respectively) of \( \sim 0.03 \) is much smaller than typical values in Class II multiple systems \((q \gtrsim 0.1; \text{Woitas et al. 2001; Manara et al. 2019})\) but similar to those of Class II binaries with planetary mass companions \((\text{e.g.,} \text{GQ Lup; Wu et al. 2017})\). Given the relatively close sky separation, structures of the disks might be affected by the dynamical interaction between the two protostars, as it is hinted in Class II sources \((\text{e.g.,} \text{Manara et al. 2019; Zurlo et al. 2020, 2021})\). A survey observation of 32 Class II disks in the Taurus star-forming region has revealed that circumstellar dust disks in multiple systems of their samples \((q \gtrsim 0.1)\) tend to be smaller than those around single sources \((\text{Manara et al. 2019})\), which may suggest that the disks in the multiple systems are truncated by the dynamical interaction \((\text{e.g.,} \text{Papaloizou & Pringle 1977; Artymowicz & Lubow 1994; Rosotti & Clarke 2018})\). The maximum disk radius in these multiple systems was \( \sim 80 \) au, and the ratio between the disk dust radius and the projected separation \((R/a)\) was always less than 0.3 \((\text{Manara et al. 2019})\). Similar trends and maximum dust disk radii have been also observed in the surveys of Class II disks in the Lupus and Ophiuchus star-forming regions \((\text{Zurlo et al. 2020, 2021})\). In these studies of Class II disks, the disk radius is defined as the radius enclosing 90% or 95% of the flux density, similar to our study.
The dust disk radius of Ced110 IRS4A is larger than the maximum dust disk radius found in the Class II multiple systems mentioned above. The ratio between the dust disk radius and the projected separation for Ced110 IRS4A ($R/a \sim 0.37$) is also larger than those reported in the Class II sources. On the other hand, the disk radius and $R/a$ of Ced110 IRS4B are in the range of those of the Class II multiple systems. These results could be due to the small stellar mass ratio of $q \sim 0.026$ observed in Ced110 IRS4. In a system with a smaller stellar mass ratio, dynamical interaction is expected to have a stronger effect on the disk around the secondary star but a less impact on the disk around the primary source (Papaloizou & Pringle 1977; Rosotti & Clarke 2018). However, it should be noted that dust disk size can be also smaller than gas disk size due to the radial drift of large dust grains (Weidenschilling 1977). This may also explain the larger dust disk of Ced110 IRS4A compared to those of the Class II multiple systems, as further radial drift would likely occur in more evolved disks. To estimate the expected truncation radius, we follow an analytic formula in Manara et al. (2019). Assuming the stellar mass ratio of 0.03 and a noneccentric orbit, we obtain truncation radii for the disks of Ced110 IRS4A and IRS4B to be $\sim 140$ au and $\sim 30$ au, respectively. The truncation radius calculated for Ced110 IRS4B is comparable with the observed dust disk radius. The expected truncation radius can be smaller approximately by a factor of 2 if we adopt an eccentricity of $\sim 0.3$ (Manara et al. 2019). Thus, the observed disk radius of Ced110 IRS4A could be also consistent with the tidal truncation if the binary orbit has an eccentricity of 0–0.3. So far, no observations have constrained the binary orbit of Ced110 IRS4. More observations that reveal the orbital motions of the protostars are required in order to evaluate how the disk is affected by the dynamical interaction of two protostars in more detail.

Although the binary orbit is unknown, the line-of-sight velocity difference of the protostars of $\sim 2.1$ km s$^{-1}$ agrees with the expected Keplerian velocity of $2.1–2.3$ km s$^{-1}$ at a radius of 250 au from Ced110 IRS4A, assuming a protostellar mass of Ced110 IRS4A of 1.21–1.45 $M_\odot$ and that the two protostars are gravitationally bound. This may suggest that the orbital plane of the binary system is close to edge-on as well as the circumstellar disks, although more observational constraints on the binary orbit, such as proper motions, are necessary for confirming this. Ced110 IRS4B is on the eastern side of Ced110 IRS4A and has a blueshifted velocity with respect to Ced110 IRS4A. Similarly, the CO isotopologue lines show blueshifted velocities on the eastern sides both of Ced110 IRS4A and IRS4B with respect to their systemic velocities. This indicates that the orbital motion of Ced110 IRS4B and the rotational motions of the disks/envelopes of Ced110 IRS4A and IRS4B are all in the same direction.

A relatively small projected separation of $\sim 250$ au can be consistent with both disk fragmentation due to gravitational instability (Adams et al. 1989; Bonnell & Bate 1994) and turbulent fragmentation of dense cores (Offner et al. 2010; Lee et al. 2019), as companions formed via turbulent fragmentation can migrate inward from thousands au to less than 100 au within a timescale of a few 10 kyr (Offner et al. 2010; Lee et al. 2019). However, the ordered rotational motions and the large difference in protostellar and disk masses in the Ced110 IRS4 system would favor disk fragmentation over turbulent fragmentation. Although the disks around the two protostars are slightly misaligned by $\sim 19^\circ \pm 0.6$, which is naturally expected in the turbulent fragmentation of dense cores (Padoan & Nordlund 2002; Bate et al. 2010; Offner et al. 2010), such small misalignment of $\leq 20^\circ$ can also appear in multiple systems formed via disk fragmentation (Stamatellos & Whitworth 2009; Bate 2018).

6. Conclusion

We have observed Ced110 IRS4, a Class 0/I protostellar system in the Chamaeleon I dark cloud, with ALMA at an angular resolutions of $\sim 0.05$ ($\sim 10$ au). The main results of our observations are as follows:

1. The observations in the 1.3 mm dust continuum emission reveal that Ced110 IRS4 is a binary system with a projected separation of $\sim 250$ au ($\sim 1.3$ ). In addition, a weak, extended emission and an arc-like structure connected to the extended emission are found at a radius of $\sim 60$ au on the northern side of the protostellar system.

2. The primary dust continuum emission associated with Ced110 IRS4A exhibits a disk-like shape with a radius of $\sim 0.485$ ($\sim 91.7$ au), and likely traces a dust disk around the protostar, as also confirmed from gas kinematics with molecular lines. The continuum emission shows no clear gaps or rings that are commonly found in Class II sources, but exhibits small bumps along its major axis with an asymmetry. The bumps can be explained by a shallow, ring-like structure at a radius of $\sim 0.42$ ($\sim 40$ au) in the dust continuum emission, as demonstrated by the intensity distribution models. This might indicate a possible, annular substructure of the dust disk. However, the dust continuum emission does not necessarily trace the surface-density structure of the disk, as it could be optically thick at the bump radii. More observations at optically thin wavelengths would confirm whether the ring-like structure originates from a substructure in the density distribution.

3. The CO isotopologue lines ($J = 2–1$) are detected around Ced110 IRS4A. These lines show velocity gradients composed of blueshifted and redshifted velocity

Table 7
Summary of Properties of the Binary System

<table>
<thead>
<tr>
<th>Source</th>
<th>$M_*$ ($M_\odot$)</th>
<th>$V_{sys}$ (km s$^{-1}$)</th>
<th>$M_{disk}$ ($M_\odot$)</th>
<th>$R_{disk}$ (au)</th>
<th>PA$_{disk}$ ($^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ced110 IRS4A</td>
<td>1.21–1.45</td>
<td>4.67 ± 0.03</td>
<td>(2.962 ± 0.001) × 10$^{-2}$</td>
<td>91.7 ± 0.2</td>
<td>103.72 ± 0.02</td>
</tr>
<tr>
<td>Ced110 IRS4B</td>
<td>0.02–0.05</td>
<td>2.69 ± 0.26</td>
<td>(6.29 ± 0.03) × 10$^{-4}$</td>
<td>33.6 ± 0.6</td>
<td>85.0 ± 0.6</td>
</tr>
</tbody>
</table>

Notes.

$^a$ Disk gas mass, calculated from the dust mass derived with a disk temperature of 20 K (Table 3) assuming a gas-to-dust mass ratio of 100.

$^b$ Radius of the dust disk.
components on the eastern and western sides of the protostar, respectively. The asymmetric intensity peaks of the 13CO and CO emission, tracing the disk emitting surfaces, suggest that the disk surface on the northern side is facing us. The PV diagrams of the C18O and 13CO emission exhibit a signature of differential rotation. The radial dependence of the rotational velocity is examined through fitting using the PV diagrams. The rotational velocity is proportional to $r^{-0.5}$ within a radius of $\sim 120$ au, which suggests the presence of a Keplerian disk. This confirms that the dust continuum emission of Ced110 IRS4A arises from a dusty disk around the protostar. The protostellar mass of Ced110 IRS4 is dynamically estimated to be $1.21 - 1.45 M_\odot$ with an inclination angle of 76\degree.

4. The dust continuum emission associated with Ced110 IRS4B has a radius of $\sim 30$ au, and exhibits three intensity peaks, though these continuum structures are marginal considering the rms noise. The PV diagram of the 13CO emission of Ced110 IRS4B shows a marginal feature of the differential rotation. Assuming Keplerian rotation, the protostellar mass is estimated to be $\sim 0.02 - 0.05 M_\odot$.

5. The C18O and SO emissions show arc-like structures and weak extended components on the north side of the protostellar system as well as the dust continuum emission. As the velocity of the arc-like structures is close to the escape velocity expected for the protostellar mass, they could be associated with shocked gas caused by an outflow.

6. The rotational motions of the disks/envelopes of Ced110 IRS4A and IRS4B, and possibly the orbital motion of Ced110 IRS4B if the two protostars are gravitationally bound, are all in the same direction, which seems to favor the binary formation scenarios of the disk fragmentation due to gravitational instability.

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Facility: ALMA.


Appendix A

Molecular Line Maps

The velocity channel maps of CO isotopologues and SO lines are presented in Figures A1–A7, and the moment zero maps of the other detected lines are shown in Figure A8. The moment zero maps are produced by integrating the emission detected above 3\sigma. The details of the maps of the other lines are summarized in Table A1.
Figure A1. Zoom-in view of the velocity channel maps of the C$^{18}$O $J = 2$–1 emission. The contour levels are 3, 5, 7, 9... ×$\sigma$, where $\sigma$ is the rms noise listed in Table 2. The dashed contours show negative emission. The crosses indicate the positions of Ced110 IRS4A and IRS4B. The labels at the top left corners denote the LSR velocities. The filled ellipse at the bottom left corner denotes the synthesized beam size.

Figure A2. Same as Figure A1 but for the $^{13}$CO $J = 2$–1 emission.
Figure A3. Same as Figure A1 but for the $^{12}$CO $J = 2$–1 emission with contour levels of 3, 6, 12, 24, ... $\times \sigma$.

Figure A4. Wide view of the velocity channel maps of the C$^{18}$O $J = 2$–1 emission. The crosses indicate the positions of Ced110 IRS4A and IRS4B. The labels at the top left corners denote the LSR velocities. The filled ellipse at the bottom left corner represents the synthesized beam size.
Figure A5. Same as Figure A4 but for the $^{13}$CO $J = 2-1$ emission.

Figure A6. Same as Figure A4 but for the $^{12}$CO $J = 2-1$ emission.
Figure A7. Same as Figure A4 but for the SO $J_N = 65 - 54$ emission.

Figure A8. Moment zero maps of the other detected lines (color) overlaid with the 1.3 mm continuum map with a robust parameter of 2.0 (contours). The color scales are in units of mJy beam$^{-1}$ km s$^{-1}$. The contour level is $3\sigma$, where $\sigma$ is 0.018 mJy beam$^{-1}$. The filled and opened ellipses at the bottom left corners represent the synthesized beam sizes of the line map and continuum map, respectively.
Appendix B

Power-law Intensity Distribution Models

Intensity distribution models that have a power-law intensity profile are examined in the same manner as described in Section 4.1.

Two types of intensity distributions, a broken power-law model and a power-law ring model, are tested. The broken power-law model is described as follows:

\[
I_c(r) = \begin{cases} 
 L \left( \frac{r_b}{r_c} \right)^{-\alpha} & (r \leq r_b), \\
 L \left( \frac{r_b}{r_c} \right)^{-\beta} \exp \left\{ - \left( \frac{r_b}{r_c} \right)^{2-\gamma} \right\} & (r > r_b), 
\end{cases}
\]

(B1)

Here, \( r \) is the radius deprojected by the inclination angle \( i \) and the position angle \( pa \), \( r_c \) is the characteristic radius where the intensity begins to decrease sharply, \( r_b \) is the break radius where the power-law index changes, \( \alpha \) is the inner power-law index, \( \beta \) is the outer power-law index, and \( \gamma \) is the power-law index determining the sharpness of the intensity cutoff at the edge. The power-law ring model, on the other hand, consists of a power-law profile and a ring component as expressed by the following equation:

\[
I_c(r) = L \left( \frac{r}{r_c} \right)^{-\beta} \exp \left\{ - \left( \frac{r}{r_c} \right)^{2-\gamma} \right\} + a_r \exp \left\{ - \frac{(r - \text{ring})^2}{2\sigma_i^2} \right\},
\]

(B2)

where \( a_r \) is the peak intensity of the ring component, \( r_r \) is the ring location in radius, and \( \sigma_i \) is the ring width. For both the broken power-law and power-law ring models, we adopt the power-law intensity profile with an exponential cutoff, which is physically motivated by a Shakura–Sunyaev disk (Shakura & Sunyaev 1973) with a power-law temperature distribution and often used to describe the disk intensity distribution. Note that, however, the intensity distribution can be connected to the physical model only when the disk is optically and geometrically thin, which would not be the case for the disk of Ced110 IRS4A at 1.3 mm. Therefore, our focus here is not to constrain the physical quantity of the disk but to demonstrate the significance of the observed bumps from a smooth intensity profile. The center of the model intensity distribution is fixed at the protostellar position in the both models. The two models are fitted to the observed continuum emission with the MCMC method. The beam convolution is calculated in every MCMC step. The best-fit parameters are summarized in Table B1.

Figures B1 and B2 show the fitting results. The broken power-law model shows systemic residuals \( \geq 6\sigma \) and \( \leq -6\sigma \) around offsets of \( \pm 0^\circ.3 \) along the major axis (B1(c)). On the other hand, the power-law ring model exhibits fewer residuals at those offsets (Figure B2(c)). Large residuals remaining around offsets of \( -0^\circ.3 \) is due to the asymmetry of the observed continuum emission, as discussed in Section 4.1. The BIC of the broken power-law and power-law ring models are calculated to be \(-38,400\) and \(-43,200\), respectively, indicating a very strong evidence that the power-law ring model better
reproduces the observations. Hence, we conclude that a model including a ring component better explains the observations than the model with a smooth intensity profile.

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