ALMA Observations of the Protostellar Disk around the VeLLO IRAS 16253–2429

Tien-Hao Hsieh1, Naomi Hirano1, Arnaud Belloche2, Chin-Fei Lee1, Yusuke Aso1, and Shih-Ping Lai1,3
1 Academia Sinica Institute of Astronomy and Astrophysics, P.O. Box 23-141, Taipei 106, Taiwan; thhsieh@asiaa.sinica.edu.tw
2 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
3 Institute of Astronomy, National Tsing Hua University (NTHU), Hsinchu 30013, Taiwan

Received 2018 September 19; revised 2018 November 14; accepted 2018 November 28; published 2019 January 24

Abstract

We present ALMA long-baseline observations toward the Class 0 protostar IRAS 16253–2429 (hereafter IRAS 16253) with a resolution down to 0″12 (~15 au). The 1.3 mm dust continuum emission has a deconvolved Gaussian size of 0″16 × 0″07 (20 au × 8.8 au), likely tracing an inclined dusty disk. Interestingly, the position of the 1.38 mm emission is offset from that of the 0.87 mm emission along the disk minor axis. Such an offset may come from a torus-like disk with very different optical depths between these two wavelengths. Furthermore, through CO (2 − 1) and C18O (2 − 1) observations, we study rotation and infall motions in this disk–envelope system and infer the presence of a Keplerian disk with a radius of 8–32 au. This result suggests that the disk could have formed by directly evolving from a first core, because IRAS 16253 is too young to gradually grow a disk to such a size considering the low rotation rate of its envelope. In addition, we find a quadruple pattern in the CO emission at low velocity, which may originate from CO freeze out at the disk/envelope midplane. This suggests that the “cold disk” may appear in the early stage, implying a chemical evolution for the disk around this proto-brown dwarf (or very-low-mass protostar) different from that of low-mass stars.

Key words: brown dwarfs – circumstellar matter – stars: individual (IRAS 16253–2429) – stars: low-mass – stars: protostars

1. Introduction

Rotationally supported disks or Keplerian disks are commonly seen in young stellar objects (YSO) at the Class II stage (Williams & Cieza 2011; Belloche 2013). Only a handful of disks have been kinematically identified at earlier evolutionary stages, at the Class I stage (Lommen et al. 2008; Takakuwa et al. 2012; Brinch and Jørgensen 2013; Chou et al. 2014; Harsono et al. 2014; Lindberg et al. 2014; Yen et al. 2014; Asó et al. 2015; Lee et al. 2016), and even rarer at the Class 0 stage (Tobin et al. 2012b; Murillo & Lai 2013; Murillo et al. 2013; Ohashi et al. 2014; Asó et al. 2017; Lee et al. 2017b, 2018). Because disks are believed to grow rapidly after the start of the core collapse (Terebey et al. 1984; Williams & Cieza 2011), star–disk systems in an embedded phase are valuable for understanding disk formation especially for that at the Class 0 stage. In addition, it is also unclear whether the disk formation channel and evolution depend on the stellar mass, for instance, whether disks form and evolve differently in brown dwarfs compared to higher-mass objects (Ricci et al. 2014; Testi et al. 2016).

IRAS 16253–2429 (hereafter IRAS 16253) was first discovered as a Class 0 source by Khanzadyan et al. (2004) in the ρ Oph star-forming region (d = 125 pc, Evans et al. 2009). Later, it was classified as a very-low-luminosity object (VeLLO) owing to its internal luminosity of ≲0.09 L⊙ (Dunham et al. 2008). Such a low luminosity implies that IRAS 16253 is an extremely young Class 0 protostar, a very-low-mass protostar, or a combination of both (Dunham et al. 2014). Using the deuterium fraction and outflow opening angle as evolutionary indicators, Hsieh et al. (2015, 2017) suggest that IRAS 16253 is a young Class 0 object. Assuming the infalling motions derived from C18O observations to be freefall, Yen et al. (2017) estimate its central mass to be 0.03 M⊙. In addition, the envelope mass has been estimated to be 0.2–0.8 M⊙ (Stanke et al. 2006; Enoch et al. 2008; Barsony et al. 2010; Tobin et al. 2012a). These results, together with the low outflow force (Hsieh et al. 2016), suggest that IRAS 16253 may form a brown dwarf or very-low-mass star depending on its future accretion. Although this substellar object unlikely hosts a sizeable protostellar disk, the integrity of its bipolar outflow implies the existence of a disk. In addition, Hsieh et al. (2018) found that IRAS 16253 has experienced a past accretion burst based on the outward shift of the CO snow line. This is believed to originate from a gravitational instability of the disk (Vorobyov et al. 2013; Vorobyov & Basu 2015).

CO and its isotopologues have been used to probe the kinematics of disks due to the brightness of their rotational transitions at submillimeter/millimeter wavelengths. With high-resolution ALMA observations, multiple CO isotopologues further provide a powerful diagnostic of their density and temperature structures (Nomura et al. 2016; Schwarz et al. 2016; Walsh et al. 2017). However, recent works find that CO could be depleted near the midplanes of the Class II disks within a few hundred astronomical units (Qi et al. 2011; Huang et al. 2017; Zhang et al. 2017; Pinte et al. 2018). This could be explained by freeze out of CO onto the dust grains or conversion of CO into less volatile molecules (Aikawa et al. 2015; van’t Hoff et al. 2017).

In this paper, we present new ALMA observations of CO, C18O, and 217 GHz continuum in the proto-brown dwarf candidate IRAS 16253. We aim to search for a disk around this unique source and study its physical and chemical properties. The observations and results are described in Sections 2 and 3, respectively. In Section 4, we detail our analyses and models of the continuum and line emission. Finally, the discussion and summary are given in Sections 5 and 6, respectively.

2. Observations

We used ALMA to simultaneously observe CO (2 − 1), C18O (2 − 1), and dust continuum emission at 217 GHz toward IRAS 16253 (α = 16h28m21.6s, δ = −24°36’23.4") on 2017
August 18th (Cycle 4 project, 2016.1.00598.S) with 42 available antennas. The total observing time was 48 minutes and the on-source time was $\approx 20$ minutes. The data were obtained in configuration of C40-7 with a projected baseline range of 11 to 2629 $\lambda$, resulting in a spatial resolution of $0'11 \times 0'08$ with uniform weighting for the continuum and of $0'14 \times 0'11$ with natural weighting for CO ($2-1$). The $^{13}$CO ($2-1$) data were combined with the ALMA cycle 2 data from Yen et al. (2017) to increase the sensitivity. However, although the $uv$-coverages overlap in these two data sets, the nonuniform sampling produces a clean beam featuring a summation of distinct large and small beam. After iterations, we selected data with a $uv$-distance shorter than 600 $\lambda$, resulting in a relatively Gaussian-like beam with a size of 0'40 by 0'37. The continuum bandwidth was 1840 MHz, centered at 217 GHz (1.38 mm). The channel width was 122 kHz (0.16 km s$^{-1}$) for CO ($2-1$) and 61 kHz (0.08 km s$^{-1}$) for $^{13}$CO ($2-1$). The rms noise level is 0.066 mJy beam$^{-1}$ for the continuum map, and 5.6 and 4.9 mJy beam$^{-1}$ for the CO and $^{18}$O maps with a channel width of 0.16 km s$^{-1}$, respectively. The bandpass, flux, and phase calibrators were J1517$-$2422, J1733$-$1304, and J1625$-$2527, respectively. A check source, J1626$-$2951, was observed for five scans spread about uniformly between the 26 scans on IRAS 16253. Self-calibration is not applied in order to maintain astrometric information of the source.

In order to compare with the 1.38 mm continuum emission, we obtained 0.87 mm data from the ALMA archive (2015.1.00741.S, PI: L. Looney). These data are obtained with a compact configuration and an extended configuration. The $uv$ range from 15 to 2031 $\lambda$ is comparable to our 1.38 mm data. The on-source time is 30 and 60 s for the compact and extended configurations, respectively. The bandwidth is 4 $\times$ 1840 MHz. The bandpass, flux, phase calibrators, and check source are J1517$-$2422, J1733$-$1304, J1625$-$2527, and J1627$-$2426, respectively, for the compact configuration and J1517$-$2422, J1517$-$2422, J1625$-$2527, and J1633$-$2557, respectively, for the extended configuration.

### 3. Results

#### 3.1. Continuum Emission at 0.87 and 1.38 mm

The continuum emission at 1.38 and 0.87 mm is found to contain two components (Figure 1). We employ a double Gaussian fit to the observed amplitude but not phase, and we find a break point at a $uv$-distance of $\approx 200$ $\lambda$ separating the extended and compact components. The fit of amplitude could introduce a bias toward positive values at high $uv$ distances when the S/N is low, but it does not significantly affect the location of the break point at the low $uv$-distance. Although the extended component shows ambiguous fitting results, the fitted compact component is consistent in position angle and aspect ratio for both wavelengths (Table 1). The minor axis aligns well with the outflow orientation ($\approx 20^\circ$, Hsieh et al. 2017) and the aspect ratio is consistent with the inclination angle derived from the outflow (Yen et al. 2017, $60^\circ$--$65^\circ$, with $0^\circ$ for pole-on). Therefore, the compact component likely traces a disk and extended components, respectively, for the extended configuration.

![Figure 1](image)

*Figure 1. $uv$-distance vs. amplitude for 0.87 mm (top) and 1.38 mm (bottom) data with the residual from the best fit. The color indicates the angles relative to the minor axis in $uv$-space, i.e., blue points close to the minor axis and red points close to the major axis. The gray area shows the best-fit two-component model, i.e., amplitudes along the minor and major axes as the upper and lower boundaries, and the solid line represents their average (Table 1). The dashed and dotted curves represent the disk and extended components, respectively. The subplot in each panel shows a zoom-in of 0--300 $\lambda$ with the vertical dashed line indicating 200 $\lambda$. (Hsieh et al. 2016). Another mechanism (Raga et al. 2009; Lee et al. 2017; Offner & Chaban 2017) is needed to explain the directional change of the outflow axis.*
Here we propose two possibilities to explain this offset: (1) the proper motion of IRAS 16253 (from 2016 August to 2017 August) and (2) the different optical depths between both wavelengths. For the first case, the projected velocity would have to be 49 mas yr$^{-1}$ ($\sim$29 km s$^{-1}$), which is much larger than that of the source in the ρ Oph region, $\lesssim$10 mas yr$^{-1}$ (Ducourant et al. 2017). However, it is noteworthy that a scenario to form brown dwarfs is the ejection velocity (Bate et al. 2002; Basu & Vorobyov 2012). The second possibility is hinted by the offset orientation, which is almost along the outflow axis; the 0.87 mm continuum emission may trace the upper layer of the inclined disk due to the high optical depth.

### 4. Analysis and Discussion

#### 4.1. Models of the Continuum Images

To explain the offset between the dust continuum peaks at 1.38 and 0.87 mm (Figure 2), we model the emission using the Monte Carlo radiative transfer code RADMC-3D$^5$ (Dullemond et al. 2012). The dust opacity $\kappa$ as a function of wavelength is constructed using DIANA Opacity Tool$^6$ (Woitke et al. 2016). The grain size distribution is assumed to follow $a(n/da \propto a^{-2}$, with a maximum size of $a_{\text{max}}$. We construct model grids (Sections 4.1.1 and 4.1.2) to perform a $\chi^2$ fitting to the visibilities at uv-distances beyond 200 kλ. The $\chi^2$ is calculated in the complex space (i.e., Equation (2) in Aso et al. 2017) with the modeled values at the uv points covered by the observations, for which the modeled visibilities are computed from the synthetic images using vis_sample.$^6$

#### 4.1.1. Model A—Flared-disk Model

Our model A assumes a flared-disk structure defined as

$$\rho(r, z) = \frac{\Sigma(r)}{\sqrt{2\pi} H(r)} \exp\left[-\frac{1}{2} \left(\frac{z}{H(r)}\right)^2\right]$$  

(1)

with

$$\Sigma(r) = \Sigma_0 \left(\frac{r}{r_0}\right)^{-1} \exp\left[-\frac{r}{R_{\text{disk}}}\right]$$  

(2)

and

$$H(r) = H_0 \left(\frac{r}{r_0}\right)^{1.3}$$  

(3)

(Harsono et al. 2015), where $r$ and $z$ are the cylindrical coordinates, $\Sigma_0$ is the disk surface density, $r_0$ is the reference radius 25 au, $R_{\text{disk}}$ is the disk radius, and $H_0$ is the scale height at $r_0$ determined by $\theta_{\text{flared}}$.

We take six free parameters including the protostellar luminosity ($L_{\text{star}}$), $M_{\text{disk}}$ (total mass of the disk scaled by $\Sigma_0$), $R_{\text{disk}}$, $\theta_{\text{flared}}$, $a_{\text{max}}$, and $a_{\text{max}}$. The central position, position angle, and inclination angle are fixed based on the 1.38 mm Gaussian fitting: an inclination angle of 65° is estimated from the Gaussian aspect ratio (Table 1). The best-fit parameters are listed in Table 2 and the images are shown in Figure 2. This fitting converged to an extreme case with $a_{\text{max}} = 150 \mu$m and $a_{\text{max}} = 3.0$ (boundary in the model grid) when it has the largest opacity ratio ($\kappa_{0.87\text{mm}}/\kappa_{1.38\text{mm}} \approx 5.5$) between 0.87 and 1.38 mm (Appendix). This result is predictable given the large offset between the 0.87 and 1.38 mm emission peaks. However, even with this large ratio, the offset (7 mas) in this model is still much smaller than the observed one (46 mas).

#### 4.1.2. Model B1/B2—Thick-disk Model

To reproduce a larger offset, we adopted the torus-like disk model from Lee et al. (2017a, 2017b) by adding an exponentially decreasing scale height beyond a radius $R_t$,

$$\rho(r, z) = \rho_0 \left(\frac{r}{R_t}\right)^{-2} \exp\left[-\frac{1}{2} \left(\frac{z}{H(r)}\right)^2\right]$$  

(4)

with

$$H(r) = \begin{cases} 
H_0 \left(\frac{r}{R_t}\right)^{1.3}, & \text{if } r < R_t, \\
H_0 \exp\left[-\left(\frac{r - R_t}{R_{\text{disk}}}\right)^2\right], & \text{if } r > R_t. 
\end{cases}$$  

(5)

In comparison to the flared-disk model, this model includes an additional free parameter, $R_t$, to determine the location of the maximum scale height. The best-fit model (Model B1) is shown in Figure 2, and the corresponding parameters are listed in Table 2. Compared to Model A, this model has a larger offset 12 mas and better reproduces the elongated shape especially at 0.87 mm because the emission from the lower surface is highly attenuated in the torus-like structure.

### Table 1

Results of UV Gaussian Fitting

| Wavelength (mm) | Extended Component | Disk Component |
|-----------------|--------------------|---------------|
|                  | Flux (mJy) | Size (mas) | P.A. (°) | Flux (mJy) | Size (mas) | P.A. (°) |
| 0.87            | 27.7 ± 3.6 | 4390 ± 330 × 2830 ± 210 | 22.9 ± 6.0 | 36.7 ± 1.9 | 190 ± 4 × 91 ± 3 | 24.9 ± 1.5 |
| 1.38            | 6.4 ± 0.4  | 1660 ± 50 × 1170 ± 30   | 9.9 ± 2.7  | 10.1 ± 0.4 | 161 ± 2 × 69 ± 2 | 21.1 ± 0.9 |

$^5$ http://www.ita.uni-heidelberg.de/~dullemond/software/radmc-3d/

$^6$ http://dianaproject.wp.st-andrews.ac.uk/data-results-downloads/fortran-package/

$^6$ The vis_sample Python package is publicly available at https://github.com/AstroChem/vis_sample or in the Anaconda Cloud at https://anaconda.org/luomis/vis_sample.
However, the offset in the synthetic images is still much smaller than the observed one.

In order to reproduce a larger offset, we defined another model, Model B2, like Model B1 but with $H_i = 5$ au. As a result, Model B2 has a larger offset of 20 mas than Model B1, but it is still smaller than the observed offset of 46 mas. Besides, this model has much larger flux densities than the observation especially at 1.38 mm.

Although Model B2/B1 cannot fit the observations well, they suggest that the offset distance can be affected by the disk density structure. Future multiwavelength observations are required to perform a better model, which should consider (1) an accurate disk center measured from optically thin emission at long wavelengths, (2) possible external heating to compute accurate flux densities, and (3) different dust components if dust settling has started.

4.2. PV-diagram and Dynamic Model

Figure 4 shows the PV diagrams of CO and C$^{18}$O along the major and minor axes centered on the 1.38 mm continuum source. The emission of both CO and C$^{18}$O emission is likely attenuated by the foreground cloud core near the systemic velocity, especially for CO. On the other hand, due to the low abundance, C$^{18}$O emission is faint in the high-velocity region where CO is bright.

We model the PV diagrams assuming a rotating infalling envelope with conservation of angular momentum. We use the radiative transfer code from Lee et al. (2014) to perform the PV model given temperature and density structures under local thermodynamic equilibrium (LTE) conditions.

We use the flared density structure (i.e., Equation (1)) with an additional free parameter $p$ adjusting its radial distribution,

$$
\rho(r, z) = \rho_0 \left( \frac{r}{r_0} \right)^{p} \exp\left[-\frac{1}{2}\left(\frac{z}{H(r)}\right)^2\right],
$$

and the temperature profile is assumed to be

$$
T(r, z) = T_0 (r/r_0)^{-0.4},
$$

where $\rho_0$ and $T_0$ scale the gas density and temperature (Lee et al. 2014; Yen et al. 2017). We take the CO abundance

---

**Figure 2.** Observed and modeled images at 0.87 and 1.38 mm (left and right columns of all panels) using only visibilities at $uv$-distances beyond 200 $\lambda$. The top panel shows the observed images with the contour levels at 5, 10, 20, 30, 45, and 60$\sigma$. The rms noise level $\sigma$ is 0.34 mJy beam$^{-1}$ (165 mK) at 0.87 mm and 0.066 mJy beam$^{-1}$ (168 mK) at 1.38 mm. The bottom panels are the three models (see the text). The top row shows the model with contours at levels of 20%, 40%, 60%, and 80% of the peak flux, the second row shows the images from synthetic observations with the same contour levels, and the bottom row shows the residuals between observations and models. The green plus sign indicates the source center from the Gaussian fitting at 1.38 mm.
relative to H$_2$ as $X_{\text{CO}} = 5 	imes 10^{-4}$ and the C$^{18}$O isotopic ratio of $X_{\text{CO}}/X_{\text{C}^{18}\text{O}} = 560$ (Wilson & Rood 1994). Because $\rho_0$ and $T_0$ determine the brightness scale and in turn are degenerate, we assume $T_0$ to be 70 K, which should not affect the fitting result of the dynamical structure. As a result, three free parameters, $\rho_0$, $p$, and $\theta_{\text{flared}}$, are used to determine the physical conditions. The rotation and radial velocities are assumed to follow the conservation of angular momentum and freefall as

$$V_{\text{rot}} = V_{\text{rot,0}} \left(\frac{r}{\rho_0}\right)^{-1.0}$$

and

$$V_{\text{infall}} = V_{\text{infall,0}} \left(\frac{r}{\rho_0}\right)^{-0.5}$$

respectively. This adds two free parameters, $V_{\text{rot,0}}$ and $V_{\text{infall,0}}$, to the model.

To compare with the observations, we convolve the modeled images with the beam of the observations and make the PV diagrams with the same PV cuts. We calculate $\chi^2$ including both major and minor axes. Because CO and C$^{18}$O trace different velocity components, they are only used at specific ranges: $|V - V_{\text{rot}}| < 1.6$ km s$^{-1}$ for C$^{18}$O and $|V - V_{\text{rot}}| > 1.6$ km s$^{-1}$ for CO. In addition, the intensity ratio between CO and C$^{18}$O cannot be well fitted due to the unknown foreground absorption, spatial filtering, and probably the isotopic ratio. Thus, we include a scaling factor, $F_{\text{C}^{18}\text{O}}$, for the C$^{18}$O emission as a free parameter in our fitting. As a result, we find $\rho_0 = 5.5 \times 10^5$ cm$^{-3}$, $F_{\text{C}^{18}\text{O}} = 52$, $p = -2.2$, $\theta_{\text{flared}} = 35^\circ$, $V_{\text{rot,0}} = 1.6$ km s$^{-1}$, and $V_{\text{infall,0}} = 1.4$ km s$^{-1}$ in our best-fit with a reduced chi-squared, $\chi^2 = 4.52$ (Figure 4). This large $F_{\text{C}^{18}\text{O}}$ and small $\rho_0$ imply that the observed CO intensity is unreasonably low. This feature can be considered as a clue of

---

**Table 2** Parameters of Disk Models

| Model | $L_{\text{int}}/10^{-2} L_\odot$ | $M_{\text{disk}}/10^{-3} M_\odot$ | $a_{\text{pow}}$ | $a_{\text{max}}/\mu$m | Disk Type | Density Pars. | $\chi^2$ | Offset Mas |
|-------|----------------|----------------|------------|----------------|----------|-------------|-----|--------|
| Model A | 2.7 ± 0.3 | 1.6 ± 0.1 | 3.0$^a$ | 150 ± 50 | flared | $\theta_{\text{flared}} = 18 \pm 1^\circ$, $R_{\text{disk}} = 9 \pm 1$ au | 1.70 | 7 |
| Model B1 | 2.1 ± 0.2 | 1.5 ± 0.1 | 3.0$^a$ | 150 ± 50 | thick | $R_{\text{disk}} = 30 \pm 2$ au, $H_t = 3.0 \pm 0.2$ au, $R_l = 7 \pm 1$ au | 1.59 | 12 |
| Model B2$^b$ | 2.1 | 2.5 | 3.0 | 150 | thick | $R_{\text{disk}} = 30$ au, $H_t = 5$ au, $R_l = 7$ au | 6.09 | 20 |

**Notes.** The error of the fitted parameters are calculated with the $\chi^2$ distribution in a confidence level of 99.9%.

$^a$ The opacity spectral index reaches the lower limit we set in the space of free parameters such that no error is provided.

$^b$ Model B2 uses the same parameters as Model B1 except for $H_t = 5$ au. The conservation of density at disk midplane ($\rho_0$ in Equation (4)) results in different total disk masses.

---

**Figure 3.** (Left) CO ($2 \rightarrow 1$) integrated intensity maps (contours) overlaid on the 1.38 mm continuum image. The contour levels are $5\sigma$, $10\sigma$, $15\sigma$, and $20\sigma$ with a rms noise level $\sigma$ of 3.0 mJy beam$^{-1}$ km s$^{-1}$ for both blue- ($0.4$–$2.6$ km s$^{-1}$) and redshifted contours ($5.8$–$8.0$ km s$^{-1}$). The white plus sign indicates the continuum source position, and the gray dashed line shows its major axis, the PV cut for Figure 4. (Right) Same as the left panel but for C$^{18}$O ($2 \rightarrow 1$). The rms noise levels are 2.7 and 2.0 mJy beam$^{-1}$ km s$^{-1}$ for the blue- and redshifted lobes, respectively. The integrated velocity ranges are 1.8–$3.3$ km s$^{-1}$ and 4.9–$5.7$ km s$^{-1}$ for blue- and redshifted contours.
CO depletion at the inner disk midplane that will be discussed later. It is noteworthy that the flared structure with $\theta_{\text{bare}}$ is required to reproduce the $^{18}\text{C}O$ emission in the upper right and bottom left quadrants in the minor-axis PV diagram (Figure 4).

4.3. CO Channel Map and CO-depletion Model

In addition to the PV diagrams, we compare the best-fit dynamic model from Section 4.2 with the observations in the CO channel maps (Figure 5). The modeled images are processed through vis_sample. To reduce the effect from unknown foreground optical depths, the intensity of the model maps was scaled channel by channel. The scaling factor of each channel was obtained by fitting the intensity of the model map with that of the observed one. In order to exclude the contamination of the outflow, the fitting was applied to the region inside the elliptical mask shown in Figure 5. The scaling factors have a mean value of 1.3 and a standard deviation of 0.4. This process does not significantly change the fitting nor the morphologies of the model. Figure 5 shows the resulting modeled images (the second column, no CO depletion) that generally fit the observation.

However, this model cannot reproduce the quadruple pattern seen in the low-velocity range between 1.8 and 2.2 km s$^{-1}$. Considering a disk with an inclination angle of 65°, this pattern might originate from (1) absorption against the optically thick dust component in the disk/envelope midplane, (2) self-absorption of the optically thick gaseous CO, and (3) depletion of CO in the disk/envelope midplane. Optically thick dust continuum emission at the disk midplane was reported in the Class 0 protostar HH212 (Lee et al. 2017a, 2017b). However, it...
Figure 5. Observed and modeled CO channel maps. The contours are plotted at 3σ, 5σ, 7σ, 10σ, and 15σ with σ of 3.3 mJy beam$^{-1}$. The first, second, and fourth columns show the contours of the observation, model without, and model with CO freeze out at the midplane, respectively. The filled contours in each of these panels show the observations for comparison. The third and fifth columns show the residuals after subtracting the model of the previous column from the observations. The elliptical gray lines indicate the mask used to fit the model. The plus sign is the continuum source center and the dashed line represents its major axis.
is unlikely to be the case for IRAS 16253 because the 1.38 mm dust emission has a relatively small size, and such absorption is not seen in the high-velocity region, $\gtrsim 2.6 \, \text{km s}^{-1}$. The second hypothesis is also unlikely because the far side (or bottom side) should be much fainter than the near side by being obscured. In this case, we would expect to see highly asymmetric emission as the dust continuum model in Section 4.1. The third possibility of CO depletion might be a reasonable explanation. CO freeze out at the disk midplane has been found in more evolved Class II sources (Qi et al. 2013, 2015; Schwarz et al. 2016; Pinte et al. 2018), but it is unclear if such cold disks appear at the early stage (van’t Hoff et al. 2018).

To mimic the CO depletion, we introduce a new free parameter, $f_{\text{snow}}$ to our model; the gas density at $z < f_{\text{snow}} \times H(R)$ is set to zero, with $f_{\text{snow}}$ between 0 (no CO depletion) and 1 (complete CO depletion). As a result, we find the best-fit CO-depletion model for $f_{\text{snow}} = 0.55$ with $\chi^2 = 1.78$ while $\chi^2 = 1.92$ for $f_{\text{snow}} = 0$. Figure 5 shows the comparison between the models with and without CO depletion. The model with CO depletion reproduces the quadruple pattern qualitatively well, though the CO peak positions are not perfectly matched and the difference between the $\chi^2$ is small.

It is noteworthy that our model of the CO channel maps cannot distinguish CO depletion from the outflow-compressed gas or the outflow cavity wall irradiated by the central source. These outflow features are commonly seen through CO (Arce & Sargent 2006). However, the velocity gradient of such gas components is usually along the outflow axes. If this is the case, the surface layers require a significantly higher excited state than the midplane while the latter likely has a higher density.

Another noticeable feature is seen in the channel maps: the orientation of the velocity gradient gradually converges into the disk major axis as the velocity increases. This can be explained as an inner Keplerian disk surrounded by an infalling rotating envelope (Aso et al. 2015). Thus, the high-velocity region could be dominated by rotation. Assuming a pure rotation at the channels $\pm 3.4 \, \text{km s}^{-1}$, we obtain a Keplerian velocity of $\approx 3.7 \, \text{km s}^{-1}$ (deprojected) at a radius of $\approx 7.8 \, \text{au}$ by fitting a Gaussian to the CO emission in the channel maps. This result, however, is in conflict with the assumption of freefall for the infall motions (Section 4.2), and will be discussed in Section 5.2.

5. Implications and Discussion

5.1. Grain Growth at the Class 0 Stage

Grain growth is believed to be the signal of planet formation (Apai et al. 2005). This process has been studied in more evolved Class II circumstellar disks (Kwon et al. 2015; Pinte et al. 2016), but is not yet fully understood at earlier evolutionary stages. Micron-sized grains could be formed in dense molecular clouds or cores (Pagani et al. 2010) and migrate into the later-formed protostellar disks. Indications of large dust grains in inner envelopes or disks around Class 0/I objects are reported based on the opacity spectral indices, $\beta$, at submillimeter/millimeter wavelengths (Jørgensen et al. 2007; Kwon et al. 2009; Chiang et al. 2012). However, formation of (sub)millimeter-sized grains requires high density such as a disk midplane (Testi et al. 2014).

Under the assumption of optically thin emission, we use the Gaussian fluxes in Table 1 to derive $\beta = 1.4$ for the extended component and $\beta = 0.9$ for the disk component assuming a dust temperature of 100 K and 30 K, respectively. These different indices imply that the dust size distribution has changed from the core to the disk; dust growth has started in the disk component. However, this analysis requires that the continuum emission at both wavelengths traces the same component. It is obviously not the case for the extended component because of the very different sizes. For the disk component, although the source structures are broadly consistent, it is still unclear whether the offset is real or not.

To mimic the CO depletion, we introduce a new free parameter, $f_{\text{snow}}$ to our model; the gas density at $z < f_{\text{snow}} \times H(R)$ is set to zero, with $f_{\text{snow}}$ between 0 (no CO depletion) and 1 (complete CO depletion). As a result, we find the best-fit CO-depletion model for $f_{\text{snow}} = 0.55$ with $\chi^2 = 1.78$ while $\chi^2 = 1.92$ for $f_{\text{snow}} = 0$. Figure 5 shows the comparison between the models with and without CO depletion. The model with CO depletion reproduces the quadruple pattern qualitatively well, though the CO peak positions are not perfectly matched and the difference between the $\chi^2$ is small.

5.2. Dynamics of the Disk–envelope System

The infall and rotation velocities of IRAS 16253 are estimated from the PV diagrams. Assuming the infall motion is a freefall motion, we estimate a central mass of $\approx 0.028 \, M_\odot$. By equalizing the gravitational force and the centrifugal force from $V_{\text{rot}}$, we found a centrifugal radius of $\approx 64 \, \text{au}$. However, our CO observations do not resolve any Keplerian rotation despite a small beam size of 15 au. A possibility is that the true disk radius is only half the centrifugal radius, i.e., the centrifugal barrier of $\approx 32 \, \text{au}$ (Sakai et al. 2014). Another explanation is that the centrifugal radius may be smaller if the infall velocity is smaller than the freefall velocity. Assuming the rotation dominates the velocity of $\pm 3.4 \, \text{km s}^{-1}$ in Figure 5, we found a deprojected Keplerian velocity of 3.7 km s$^{-1}$ at a radius of 7.8 au. We then estimate a mass of the central star of 0.12 $M_\odot$ (Section 4.3), such that the centrifugal radius is $\approx 16 \, \text{au}$ and centrifugal barrier is $\approx 8 \, \text{au}$. In such a case, the infall velocity would be 50% smaller than the freefall velocity. These two possibilities are not in conflict with each other, and the true system could be a mix of them. Therefore, we speculate that the radius of the Keplerian disk is in between 8 and 32 au.

5.3. The Disk Size and Disk Growth

Only a small number of Class 0 protostellar disks have been kinematically identified while it is crucial to understand the disk formation. Our dynamical analysis suggests a Keplerian disk with a radius of $8–32 \, \text{au}$ in the Class 0 source IRAS 16253. This result also broadly agrees with the size of the dusty disk 9–30 au (Table 2).

Disk formation has not yet been fully understood, and two scenarios are proposed to explain the growth of the Keplerian
disk radius: (1) “early-start, slow-growth” or (2) “slow-start, rapid-growth” (Yen et al. 2017; Lee et al. 2018). In the classical picture, i.e., “slow-start, rapid-growth,” the growth of the disk radius in a nonmagnetized collapsing core is:

\[
\rho_{\text{kep}}(\text{au}) \sim 0.25 \left( \frac{\Omega}{10^{-14} \text{ rad s}^{-1}} \right)^{2} \left( \frac{a}{0.2 \text{ km s}^{-1}} \right) \left( \frac{t}{10^{5} \text{ yr}} \right)^{3},
\]

(10)

where \( \Omega \) is the initial cloud core rotation rate, \( a \) is the sound speed, and \( t \) is the time since the core collapse (Terebey et al. 1984; Belloche 2013). IRAS 16253’s cloud core rotation rate has been measured to be 3.5–4.1 km s\(^{-1}\) pc\(^{-1}\), which is relatively small among 17 Class 0/I objects (median: 8.1 - 10.7 km s\(^{-1}\) pc\(^{-1}\), Tobin et al. 2011). In addition, it has the smallest N\(_2\)H\(^+\) line width (<0.2 km s\(^{-1}\)) compared with other VeLLOs (Hsieh et al. 2015, 2018), implying a very small sound speed. Such properties suggest that the disk in IRAS 16253 might grow relatively slowly. If we use \( \Omega = 1.8 - 2.1 \times 10^{-14} \text{ rad s}^{-1} \) (Tobin et al. 2011) and \( a = 0.14 \text{ km s}^{-1} \) (Hsieh et al. 2018), it takes \( 2.5 - 3.7 \times 10^{5} \text{ yr} \) to form a disk with \( \rho_{\text{kep}} = 8 - 32 \text{ au} \). However, it is unrealistic because IRAS 16253 is considered to be much younger due to its small mass fraction of the star+disk (0.03 – 0.12 \( M_{\odot} \)) to the core (0.2–0.8 \( M_{\odot} \); Stanke et al. 2006; Enoch et al. 2008; Barsony et al. 2010; Tobin et al. 2012a); this fraction may suggest an age of \( \leq 0.5 \times 10^{5} \text{ yr} \) in the nonmagnetized collapsing model (Young & Evans 2005). Thus, the disk of IRAS 16253 seems to favor the “early-start, slow-growth” scenario that is supported by the analysis of the properties of the Class 0 source HH211 (Lee et al. 2018).

A possible explanation for this scenario might be passing through a rotating first hydrostatic core (FHSC) with a size of a few astronomical units and a lifetime of a few thousand years (Larson 1969). Theoretical models suggest that a rapidly rotating FHSC may directly evolve into a circumstellar disk after the collapse (Bate 2011; Machida & Matsumoto 2011). However, given IRAS 16253’s small cloud rotation rate, the disk size after the collapse should still be as small as a few astronomical units. High-angular-resolution observations are needed to resolve the size of the Keplerian disk and examine this disk formation process.

5.4. Freeze Out of CO in the Protostellar Disk

CO depletion is considered as the most plausible explanation for the quadruple pattern in the channel maps although the other hypotheses cannot be completely ruled out. The freeze out of CO would suggest a temperature below 20 K, the CO sublimation temperature, in the midplane of the disk or the inner envelope. This kind of “cold disk” had not yet been found around protostars at an early embedded stage. Harsono et al. (2015) found that, unlike more evolved Class II disks, embedded disks can be heated by viscous accretion and stay warm due to the inefficient radiative cooling in the optically thick envelope. Such a picture is confirmed toward a borderline Class 0/I protostar, L1527; it shows gaseous CO throughout the disk without detection of N\(_2\)D\(^+\) which is abundant when CO is frozen out (van’t Hoff et al. 2018). The CO freeze out in IRAS 16253 may result from its unique low internal luminosity as a VeLLO, providing low radiative heating. In addition, the disk/envelope midplane could be shielded or self-shielded from heating by the central protostar given the optically thick disk (Section 4.1), as seen in VLA1623 (Murillo et al. 2015).

It is also noteworthy that IRAS 16253 has experienced a past accretion burst that temporally enhanced the protostellar luminosity and sublimated CO within a radius of \(~1250 \text{ au}\) (Hsieh et al. 2018). The CO freeze-out timescale is a function of dust temperature, \( T_{\text{d}} \), and gas density, \( n_{\text{H}_2} \),

\[
\tau_{\text{kep}} = 1 \times 10^{4} \left( \frac{T_{\text{d}}}{10^5 \text{ K}} \right)^{-0.6} \left( \frac{n_{\text{H}_2}}{10^3 \text{ cm}^{-3}} \right)^{0.4} \text{ yr}
\]

(Visser & Bergin 2012). Thus, if the gas density in the depletion region is \( >10^7 \text{ cm}^{-3} \), it requires \(~<1000 \text{ yr}\) for CO to refreeze out. In addition, since the envelope is infalling, the gas might have migrated from the outer region into the inner region. For example, the CO frozen-out gas at \( r \sim 15 \text{ au} \) could have migrated from \( r \sim 100 \text{ au} \) assuming an infalling velocity of \( 1 \text{ km s}^{-1} \) in 500 yr. Therefore, if the density structure is resolved, a chemical-dynamical model would allow us to measure the time since the last accretion burst.

6. Summary

We present ALMA long-baseline observations toward the Class 0 source IRAS 16253–2429. We summarize our results in the following:

1. A compact source is detected from the continuum emission at both 0.87 and 1.38 mm. An offset of \(~46 \text{ mas}\) is found between the continuum emission peaks at 0.87 and 1.38 mm although a calibration issue cannot be completely ruled out. This offset along the outflow axis could originate from the different optical depths in an inclined disk. However, it requires a very large \( \kappa \) ratio between these two wavelengths. The largest ratio we can reproduce is \(~5.7 \text{ at } d_{\text{max}} = 150 \mu \text{m} \) and \( \kappa_{\text{pow}} = 3.0 \), for which \( \kappa_{\text{pow}} = 3.0 \) is the minimum in our parameter space. Our model does generate an offset of 10–20 mas, but it is still smaller than the observed value.

2. Rotation and infall motions are detected through CO and C\(^{18}\)O (2 – 1) emission toward the disk–envelope system. Assuming the infall motion is freefall, we estimate the central stellar mass to be \(~0.03 \text{ } M_{\odot} \). However, the rotation motion implies a mass of \(~0.12 \text{ } M_{\odot} \), and in this case, the infall velocity is reduced by \(~50\%\) from freefall. Further observations are required to test these two possibilities, and help to answer if IRAS 16253 will form a brown dwarf (<0.08 \( M_{\odot} \)) or a normal low-mass star in the future.

3. The best-fit dynamical model has a centrifugal radius of \(~64 \text{ au}\), but the Keplerian rotation is not resolved by the current resolution of 15 au. Deriving from the rotation dominated region, we estimate a centrifugal radius of 16 au. Together with the size from the dust continuum, we speculate that a Keplerian disk is present with a radius of \(~8–32 \text{ au}\) in IRAS 16253.

4. The presumed disk radius, 8–32 au, is much larger than that derived from the classical nonmagnetized collapsing model given the small cloud core rotation rate and sound speed in IRAS 16253. Therefore, the circumstellar disk in...
IRAS 16253 may have directly evolved from a rotating FHSC, as suggested by theoretical models.

5. The quadruple pattern in the CO channel maps at low velocities could be explained by freeze out of CO in the disk midplane. The presence of such a “cold disk” may result from the faint luminosity of the protostar. Besides, the dense inner disk, as indicated by the continuum images, might shield the outer region or be self-shielding from the central heating source.

We are thankful for the anonymous referee for many insightful comments that helped to improve this paper significantly. The authors thank Dr. Hsi-Wei Yen, for providing valuable discussions. We thank Dr. Attila Juhasz for helping us run the RADMC-3D code. We are thankful for the help from the ALMA Regional Center in Taiwan. This paper makes use of the following ALMA data: ADS/JAO. ALMA#2016.1.00598.S, 2013.1.00879.S, and 2015.1.00741.

S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), MoST and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO, and NAOJ. N.H. acknowledges a grant from the Ministry of Science and Technology (MoST) of Taiwan (MoST 107-2119-M-001-029). S.P.L. acknowledges support from the Ministry of Science and Technology of Taiwan with Grant MOST 106-2119-M-007-021-MY3.

Software: RADMC-3D (Dullemond et al. 2012), DIANA Opacity Tool (Woitke et al. 2016), vis_sample (https://github.com/AstroChem/vis_sample).

Appendix

Opacity Model

The dust opacity used in the continuum model (Section 4.1) was obtained from the DIANA Opacity Tool (Woitke et al. 2016). The DIANA opacity tool computes fast models of the dust opacity κ as a function of wavelength. Dust opacities for absorption κ_{abs} and scattered κ_{sca} are derived and are used in the RADMC-3D code. Figure 6 shows the summation of κ_{abs} and κ_{sca} with different maximum sizes of dust. An extreme case with the maximum opacity ratio between 0.87 and 1.38 mm is found (κ_{0.87mm}/κ_{1.38mm} ≈ 5.5) when a_{max} = 150 μm and a_{pow} = 3.0. We note that this ratio corresponds to an index β ≈ 4.2 that is even larger than that in the interstellar medium. However, this index was measured between 0.87 and 1.38 mm. It may not be representative of the index over a broader wavelength range.

ORCID iDs

Tien-Hao Hsieh @ https://orcid.org/0000-0002-5507-5697
Naomi Hirano @ https://orcid.org/0000-0001-9304-7884
Arnaud Belloche @ https://orcid.org/0000-0003-0046-6217
Chin-Fei Lee @ https://orcid.org/0000-0002-3024-5864
Yusuke Aso @ https://orcid.org/0000-0002-8238-7709
Shih-Ping Lai @ https://orcid.org/0000-0001-5522-486X

Figure 6. Dust opacity as a function of wavelength for the dust size distribution with a power-law index of 3.0 (top) and 3.5 (bottom). The colored solid lines show models with different maximum dust sizes. The thick dashed line represents the model with thin ice grain coagulated at a density of 10^{6} cm^{-3} (Ossenkopf & Henning 1994) as a reference. The two vertical dashed lines indicate the observed wavelengths, 0.87 and 1.38 mm, in this paper.
