An Asymmetric Dust Ring around a Very Low Mass Star ZZ Tau IRS

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Abstract

We present Atacama Large Millimeter/submillimeter Array (ALMA) gas and dust observations at band 7 (339 GHz: 0.89 mm) of the protoplanetary disk around a very low mass star ZZ Tau IRS with a spatial resolution of 0.25″. The 12CO J = 3 → 2 position–velocity diagram suggests a dynamical mass of ZZ Tau IRS of ~0.1–0.3 M☉. The disk has a total flux density of 273.9 mJy, corresponding to an estimated mass of 24–50 M⊕ in dust. The dust emission map shows a ring at r = 58 au and an azimuthal asymmetry at r = 45 au with a position angle of 135°. The properties of the asymmetry, including radial width, aspect ratio, contrast, and contribution to the total flux, were found to be similar to the asymmetries around intermediate mass stars (~2 M☉) such as MWC 758 and IRS 48. This implies that the asymmetry in the ZZ Tau IRS disk shares a similar origin with others, despite the star being ~10 times less massive. Our observations also suggest that the inner and outer parts of the disk may be misaligned. Overall, the ZZ Tau IRS disk shows evidence of giant planet formation on a ~10 au scale at a few megayears. If confirmed, it will challenge existing core accretion models in which such planets have been predicted to be extremely hard to form around very low mass stars.

Unified Astronomy Thesaurus concepts: Planetary-disk interactions (2204); Protoplanetary disks (1300)

1. Introduction

Core accretion planet formation theories predict that only terrestrial and icy planets can form around very low mass (VLM) stars (≤0.1–0.2 M☉), and the formation of gas giant planets is essentially prohibited (e.g., Liu et al. 2019, 2020; Matsumoto et al. 2020; Miguel et al. 2020). The reasons are multifold. First, a low stellar mass results in longer dynamical timescale and longer growth timescale of dust, delaying the formation of planetary cores. Second, the mass of dust in protoplanetary disks, the building blocks of planets, is correlated with stellar mass (e.g., Ansdell et al. 2017). A low dust mass in disks around VLM stars leads to low mass of protoplanets, suppressing pebble accretion (Ormel & Liu 2018) and preventing cores from ever reaching the critical mass to trigger runaway gas accretion. Last but not least, observed stellar accretion rates suggest that disks around VLM stars evolve faster than those around higher mass stars, further daunting the task of planet formation (Manara et al. 2012; Liu et al. 2020). In addition, a water snowline has been proposed to be the preferred site of planetesimal and planet formation due to its enhanced local dust-to-gas ratio (Ormel 2017). Around VLM stars, snowline is close to the star at r ~ 0.1 au. Therefore compact systems with rocky planets like the TRAPPIST-1 (Gillon et al. 2016) are expected, while planet formation at r ≥ 1 au is not (Miguel et al. 2020).

Indeed, statistical studies show that at small orbital separations rocky and icy planets are common around M dwarfs (e.g., Dressing & Charbonneau 2015), while the occurrence rate of gas giant planets dives from 14% around 2 M☉ stars to 3% around 0.5 M☉ stars (Johnson et al. 2010). Around VLM stars, only a handful of gas giant planets have ever been found (e.g., GJ 3512; Morales et al. 2019), and their formation mechanism is a mystery. Since their host stars are mature main-sequence stars that finished planet formation long before, it is unclear where and when those planets form. Protoplanetary disks around VLM stars serve as excellent laboratories for investigating planet formation in these extreme environments.

The Atacama Large Millimeter/submillimeter Array (ALMA) has revealed a variety of substructures in protoplanetary disks, such as rings, gaps, cavities, spirals, and crescent structures. While rings/gaps are the most common (e.g., Andrews et al. 2018; Long et al. 2018; Cieza et al. 2021), roughly 10 disks show azimuthal asymmetries (e.g., Cieza et al. 2017; Dong et al. 2018b; Pérez et al. 2018; Tsukagoshi et al. 2019; Francis & van der Marel 2020; van der Marel et al. 2021). Disks around VLM stars also harbor rings and gaps (e.g., Kurtovic et al. 2021); however, azimuthal asymmetries have not yet been reported. Asymmetric dust crescents may be local dust traps at gas pressure maxima (e.g., Raettig et al. 2015; Ragusa et al. 2017), and thus ideal locations of planet formation (e.g., Chang & Oishi 2010). Three possible origins of asymmetries have been discussed by van der Marel et al. (2021): (a) long-lived anticyclonic vortices at gap edges, possibly opened by companions (e.g., Raettig et al. 2015), (b) gas horseshoes at the edge of eccentric cavities curved by massive companions (e.g., Ragusa et al. 2017), and (c) part of spiral arms (van der Marel et al. 2016) triggered by companions. The main difference between the former two is in the mass of the companions: a vortex can be produced at the edges of gaps opened by planets as low mass as super-Earths (Dong et al. 2018a), whereas a horseshoe needs to be triggered by a much more massive companion, i.e., a brown dwarf. Overall, all three mechanisms suggest the presence of companions (planets) inside the cavity or gap.

In this paper, we report a ring and an asymmetric structure around the VLM star ZZ Tau IRS (spectral type: M4.5–M5, T eff: 3015–3125 K, L star: 0.02–0.13 L☉, M star: 0.09–0.16 M☉, White & Hillenbrand 2004; Andrews et al. 2013; Herczeg & Hillenbrand 2014) in the Taurus star-forming region at an
The synthesized dust continuum image of the combined data is shown in Figure 1. In the CLEAN task, we set the uv-taper (0.4 × 500.0 MÅ at PA of 48°) with a robust parameter of −2.0 to obtain a nearly circular beam, and we did not use the “multiscale” option. The rms noise in the region far from the source is 268 μJy beam−1 with a beam size of 254 × 248 mas at a position angle (PA) of −61°7.

The 12CO J = 3 → 2 line data (Table 1) were extracted by subtracting the continuum in the uv plane using the uvccontsub task in the CASA tools. A line image cube with a channel width of 0.5 km s−1 was produced by the CLEAN task. The integrated line flux map (moment 0) and the intensity-weighted velocity map (moment 1) are shown in Figure 2. The channel maps at +1.0 to +13.0 km s−1 are shown in Figure 7 in Appendix C. The rms noise in the moment 0 map is 61.4 μJy beam−1 km s−1 with a beam size of 283 × 156 mas at a PA of −50°2, and the rms noise in the moment 1 map is 9.56 μJy beam−1 at 0.5 km s−1 bin. The peak signal-to-noise ratio (S/N) is 24.1 in the channel map of +4.0 km s−1.

## 3. Results

### 3.1. Dust Continuum Emission

Figure 1 shows dust continuum images of the ZZ Tau IRS disk in band 7, as well as its radial and azimuthal profiles. We found two structures: a ring at r ∼ 50 au (hereafter we refer to the ZZ Tau IRS disk as a “ring”) in Figure 1(b) and an azimuthal asymmetry with a contrast ratio of 1.39 ± 0.05 between its peak and the opposite side on the ring in Figure 1(c). The peak S/N in the ring is 78.4. The dust continuum image synthesized with only the imaginary part (which efficiently detects asymmetric structures) indicates that the asymmetric structure in the ring is significant with a peak S/N of 34.3 in the central panel in Figure 6 in Appendix B. In the azimuthal profile (Figure 1(c)), we found two peaks at PAs of ∼130° and ∼310°. Such a two-peak structure along a disk major axis is commonly found in low spatial resolution images of rings (∼0°2–0°4; e.g., Ansell et al. 2016). Our visibility analyses in Section 4 suggest that the peak at a PA of ∼310° is caused by beam effects. Hereafter we refer to the peak at a PA of ∼130° as the asymmetry.

### 2. ALMA Archive Data

We used the ALMA archive data at band 7 (program ID: 2016.1.01511.S, PI: J. Patience), summarized in Table 1. The data were calibrated by the Common Astronomy Software Applications (CASA) package (McMullin et al. 2007), following the calibration scripts provided by ALMA. We performed a self-calibration of the visibilities. The phases were self-calibrated once, with fairly long solution intervals (solint = “inf”) that combined all spectral windows. To facilitate analyses later (Section 4), we shifted the observed dust continuum images to minimize the asymmetry relative to the phase center using the procedure described in Appendix B.

| Observations                  | Dust continuum |
|-------------------------------|----------------|
| Observing date (UT)           | 2017 Jul 6     |
| Project code                  | 2016.1.01511.S |
| Time on source (minutes)      | 4.5            |
| Number of antennas            | 42             |
| Baseline lengths              | 16.7 m–2.6 km  |
| Baseband Freqs. (GHz)         | 331.9 (cont.)  |
| Channel width (MHz)           | 15.6           |
| Continuum bandwidth (GHz)     | 15.6           |
| Bandpass calibrator           | J0510+1800     |
| Flux calibrator               | J0510+1800     |
| Phase calibrator              | J0438+3004     |
| Typical PWV (mm)              | 0.60           |

The final synthesized dust continuum image of the combined data is shown in Figure 1. In the CLEAN task, we set the uv-taper (0.4 × 500.0 MÅ at PA of 48°) with a robust parameter of −2.0 to obtain a nearly circular beam, and we did not use the “multiscale” option. The rms noise in the region far from the source is 268 μJy beam−1 with a beam size of 254 × 248 mas at a position angle (PA) of −61°7.

The 12CO J = 3 → 2 line data (Table 1) were extracted by subtracting the continuum in the uv plane using the uvccontsub task in the CASA tools. A line image cube with a channel width of 0.5 km s−1 was produced by the CLEAN task. The integrated line flux map (moment 0) and the intensity-weighted velocity map (moment 1) are shown in Figure 2. The channel maps at +1.0 to +13.0 km s−1 are shown in Figure 7 in Appendix C. The rms noise in the moment 0 map is 61.4 μJy beam−1 km s−1 with a beam size of 283 × 156 mas at a PA of −50°2, and the rms noise in the moment 1 map is 9.56 μJy beam−1 at 0.5 km s−1 bin. The peak signal-to-noise ratio (S/N) is 24.1 in the channel map of +4.0 km s−1.

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Figure 1. Synthesized image of the dust continuum for the ZZ Tau IRS ring obtained from band 7. (a) Entire image. The rms noise measured in the region far from the object is 0.268 mJy beam$^{-1}$ with a beam size of 254 × 248 mas at a PA of −61.7. (b) Radial cut along the disk major axis at a PA of 135° in panel (a). (c) Azimuthal profile along the elliptical ring in panel (a). Two peaks are found at PAs of −130° and −310°. Only the peak at a PA of −130° is a real asymmetry, whereas that at PA of −310° is an apparent structure due to a low spatial resolution effect (see Section 4).

The total flux density of the dust continuum derived from visibility analyses in Section 4 is 273.9 ± 27.4 mJy (Table 2), assuming a 10% uncertainty in the absolute flux calibration, consistent with previous single-disk observations (300 ± 40 mJy; Di Francesco et al. 2008). The peak brightness temperature in the ring calculated from the best-fit model in the visibility analyses (Section 4) is 14.9 ± 0.9 K assuming a 10% uncertainty in the absolute flux calibration.

We now estimate the physical properties of the dust ring. The optical depth $\tau_{\nu}$ is calculated as:

$$ I_{\nu} = B_{\nu}(T_{\text{mid}}) \{ 1 - \exp(-\tau_{\nu}) \}, $$

where $I_{\nu}$, $B_{\nu}$, and $T_{\text{mid}}$ are the intensity, the Planck function, and the midplane temperature, respectively. We use the midplane temperature profile with a simplified expression for a passively heated, flared disk in radiative equilibrium (e.g., Dullemond et al. 2001):

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

where $L_{*}$ is the stellar luminosity (0.017–0.113 $L_{\odot}$), $\phi$ is the flaring angle, and $\sigma_{SB}$ is the Stefan–Boltzmann constant. If the starlight-absorbing small dust grains (sub-micron-sized) have a similar spatial distribution to the large dust grains (millimeter-sized) traced by millimeter emission (similar to the PDS 70 disk; Hashimoto et al. 2012; Keppler et al. 2019), the inner wall of the ring is directly exposed to stellar radiation, and $\phi$ reaches unity. In this case, at $r = 45$ au where the asymmetry is located (see visibility analyses in Section 4), Equation (2) yields $T_{\text{mid}} = 17.8$–28.6 K (uncertainty due to the stellar luminosity). The corresponding optical depth $\tau_{\nu}$ is 0.5–1.4 based on Equation (1). Therefore, the asymmetry is marginally optically thin. The rest of the ring is expected to be optically thinner. Approximating the entire disk as an optically thin structure, the total flux corresponds to a total mass (gas + dust) of 7.6–15.7 $M_{\text{Jup}}$ assuming the dust temperature of $T_{\text{mid}} = 17.8$–28.6 K, an opacity per unit dust mass of $\kappa_{\nu} = 3.45 \text{ cm}^{2} \text{ g}^{-1}$ at 345 GHz (Beckwith & Sargent 1991), and a gas-to-dust mass ratio of 100. We note that the dust mass estimate is a lower limit since the actual dust temperature can be lower. The large dust grains are expected to concentrate at the pressure peak outside the cavity wall and reach a temperature lower than that estimated using Equation (2) with $\phi \sim$ unity. In the extreme case, the observed cavity in large dust grains may even be filled with small dust grains (e.g., “missing cavities”; Dong et al. 2012), resulting in substantially lower temperature at the ALMA ring location.

### 3.2. Gas Emission

The integrated line flux map of $^{12}$CO $J = 3 \rightarrow 2$ in Figure 2(a) shows a single-peak structure with a peak flux of 1.0 ± 0.1 Jy beam$^{-1}$ km s$^{-1}$ at 16.3$\sigma$ and a total flux above 3$\sigma$ of 1.9 ± 0.19 Jy km s$^{-1}$ assuming a 10% uncertainty in the absolute flux calibration. As shown in the channel maps in Figure 7 in Appendix C, the $^{12}$CO emission is absorbed at 6.5–7.0 km s$^{-1}$, and thus the total flux could be a lower limit. The brightness temperature map of $^{12}$CO converted from the moment 8 map (maximum values of the spectrum) is shown in Figure 2(b). Since $^{12}$CO $J = 3 \rightarrow 2$ could be generally optically thick, it could be a good tracer for the gas temperature in the emitting region. At the location of the asymmetry, the brightness temperature of $^{12}$CO is ~35 K, higher than the 17.8–28.6 K estimated by Equation (2). This could be because the emitting surface of $^{12}$CO is in the upper hotter layer of the disk. Figure 2(d) shows the $^{12}$CO position–velocity (PV) diagram (channel maps: Figure 7 in the Appendix C) along PA = 135°. We overplotted the loci of the peak emission of a Keplerian disk with an inclination of 60° (see Section 4) around a central star with masses of 0.1, 0.2, and 0.3 $M_{\odot}$, and found that the dynamical mass of ZZ Tauri IRS is ~0.1–0.3 $M_{\odot}$. This value is consistent with the spectroscopically determined mass (0.1–0.2 $M_{\odot}$; Andrews et al. 2013;
Herczeg & Hillenbrand 2014. Note that we assume that the systemic velocity of ZZ Tau IRS is 6.5 km s$^{-1}$ in the PV diagram.

4. Visibility Analyses

Since the contrast of the asymmetry in the ZZ Tau IRS ring is of order unity, an imaging artifact such as a sidelobe of the bright ring could generate an apparent asymmetry. To characterize the disk structure, we performed forward modeling in which the observed visibilities are reproduced with a parametric model of the ring in the visibility domain.

The ZZ Tau IRS disk is assumed to consist of a ring and an asymmetry. The model ring consists of a narrow Gaussian ring (ring A) superposed on a wide Gaussian ring (ring B) as shown in Figure 3(a), and is described as follows:

$$I_{\text{ring}}(r) \propto \exp\left(\frac{-(r - r_{\text{peak,ringA}})^2}{2\sigma_{r,\text{ringA}}^2}\right)$$

$$+ \delta \exp\left(\frac{-(r - r_{\text{peak,ringB}})^2}{2\sigma_{r,\text{ringB}}^2}\right).$$

Figure 2. Synthesized images of the $^{12}$CO $J = 3 \rightarrow 2$ emission line for the ZZ Tau IRS ring. (a) $^{12}$CO moment 0 map. The rms noise is 61.4 mJy beam$^{-1}$ km s$^{-1}$ with a beam size of 283 × 156 mas at a PA of $-50^\circ$. (b) $^{12}$CO moment 8 map converted to the brightness temperature. (c) $^{12}$CO moment 1 map. The rms noise is 9.56 mJy beam$^{-1}$ km s$^{-1}$ bin. The dotted contours represent the dust continuum at 10σ, 30σ, and 50σ. (d) PV diagram along a PA of $135^\circ$ taken from Section 4. The three lines denote loci of the peak emission of a Keplerian disk with a disk inclination of 60° around 0.1–0.3 $M_\odot$ stars at $d = 130.7$ pc. The systemic velocity (white dotted line) is assumed to be 6.5 km s$^{-1}$.
Parentheses describe parameter ranges in our MCMC calculations. Note. Black dotted contours represent the dust continuum image at 10 µm. Observed data are the same as those in Figures 1(b) and (c). Panel (d): best-fit model image (3″ × 3″). Panel (e): residual image (6″ × 6″). The reduced-χ² is 1.91. The black dotted contours represent the dust continuum image at 10µm, 30µm, and 50µm.

Figure 3. Panel (a): azimuthally averaged radial surface brightness for the best-fit model with a raw resolution. The asymmetry is not included in this panel. Panels (b) and (c): radial and azimuthal profiles of the observations and the best-fit model convolved with the beam in observations of 254 × 248 mas at a PA of −61°. Observed data are the same as those in Figures 1(b) and (c). Panel (d): best-fit model image (3″ × 3″). Panel (e): residual image (6″ × 6″). The reduced-χ² is 1.91. The black dotted contours represent the dust continuum image at 10µm, 30µm, and 50µm.

| Panel | Description |
|-------|-------------|
| (a)   | Radial location (au) vs. Normalized surface brightness |
| (b)   | Observed data vs. Model data |
| (c)   | Position angle (deg) vs. Normalized surface brightness |
| (d)   | Best fit model image (raw resolution) |
| (e)   | Residual image (6″ × 6″) |

Table 2

| Parameter | Value |
|-----------|-------|
| r_{peak,ringA} (au) | 57.51^{+0.19}_{-0.18} |
| FWHM_{ringA} (au) | 41.08^{+0.63}_{-0.40} |
| r_{peak,ringB} (au) | 83.6^{+1.6}_{-1.67} |
| FWHM_{ringB} (au) | 133.65^{+1.39}_{-1.42} |
| δ (deg) | 0.34^{+0.01}_{-0.01} |
| i (deg) | 60.16^{+0.07}_{-0.07} |
| PA (deg) | 134.73^{+0.09}_{-0.09} |
| F_{total} (mJy) | 273.94^{+0.64}_{-0.60} |
| F_{asym} (mJy) | 14.51^{+0.25}_{-0.24} |
| r_{peak,asym} (au) | 45.15^{+0.22}_{-0.21} |
| θ_{peak,asym} (deg) | -18.17^{+0.52}_{-0.52} |
| FWHM_{asym} (au) | 11.31^{+0.08}_{-0.07} |
| FWHM_{PA,asym} (deg) | 103.07^{+1.59}_{-1.40} |

Note. Parentheses describe parameter ranges in our MCMC calculations.

### Table 2

| Column 1 | Column 2 | Column 3 | Column 4 | Column 5 | Column 6 |
|----------|----------|----------|----------|----------|----------|
| r_{peak,ringA} | 57.51^{+0.19}_{-0.18} | 41.08^{+0.63}_{-0.40} | 83.6^{+1.6}_{-1.67} | 133.65^{+1.39}_{-1.42} | 0.34^{+0.01}_{-0.01} | 60.16^{+0.07}_{-0.07} | 134.73^{+0.09}_{-0.09} |
| F_{total} | 273.94^{+0.64}_{-0.60} | 14.51^{+0.25}_{-0.24} | 45.15^{+0.22}_{-0.21} | -18.17^{+0.52}_{-0.52} | 11.31^{+0.08}_{-0.07} | 103.07^{+1.59}_{-1.40} |

where r_{peak,ringA}, σ_{r,ringA}, r_{peak,ringB}, σ_{r,ringB}, and δ are the radial peak positions and standard deviations of two Gaussian rings and a scaling factor between the two, respectively. The width of the ring (FWHM) is calculated as 2.355σ_{ringA}.

The asymmetry is defined as an elliptical Gaussian function in polar coordinates as follows:

\[ I_{asym}(r, \theta) \propto \exp \left( -\frac{(r - r_{peak,asym})^2}{2\sigma_{r,asym}^2} - \frac{(\theta - \theta_{peak,asym})^2}{2\sigma_{\theta,asym}^2} \right), \]  

where r_{peak,asym}, θ_{peak,asym}, σ_{r,asym}, and σ_{θ,asym} are the radial peak position, azimuthal peak position, radial standard deviation, and azimuthal standard deviation, respectively. The flux for the asymmetry is normalized to F_{asym}. The combined model image is magnified and rotated with an inclination (i) and a PA. The total flux for the combined model image is normalized to F_{total}. The radial and azimuthal widths (FWHM) of the asymmetry are 2.355σ_{r,asym} and 2.355σ_{θ,asym} respectively. In total, there are 13 free parameters in our model (F_{total}, F_{asym}, r_{peak,ringA}, σ_{r,ringA}, r_{peak,ringB}, σ_{r,ringB}, δ, r_{peak,asym}, θ_{peak,asym}, σ_{r,asym}, σ_{θ,asym}, i, and PA).
The model image was converted to visibility measurements with the public Python code vis_sample (Loonis et al. 2017), in which model visibilities are samples with the same (u, v) grid points as the observations. The model visibilities are deprojected7 with the system PA and i as free parameters. The fitting is performed with the Markov Chain Monte Carlo (MCMC) method in the emcee package (Foreman-Mackey et al. 2013). The log-likelihood function lnL in visibility analyses is

\[
\ln L = -0.5 \sum_j W_j \left( \left( V_j^{\text{obs}} - V_j^{\text{model}} \right)^2 + \left( \text{Im} V_j^{\text{obs}} - \text{Im} V_j^{\text{model}} \right)^2 \right),
\]

where the subscript j represents the jth data. \( V_j^{\text{obs}} \) and \( V_j^{\text{model}} \) are observed and model visibilities and weights corresponding to \( 1/\sigma_j^2 \) (\( \sigma_j \) is the rms noise of a given visibility; see details in CASA Guides8), respectively. The values of \( V_j^{\text{obs}} \) and \( W_j \) (i.e., \( 1/\sigma_j^2 \)) are provided in the measurement set of ALMA data. Our calculations used flat priors with the parameter ranges summarized in Table 2. We ran 3000 steps with 100 walkers, and discarded the initial 1000 steps as the burn-in phase based on trace plots in Figure 8 in Appendix D.

The fitting results with uncertainties computed from the 16th and 84th percentiles, the radial profile of best-fit surface brightness for the ring with a raw resolution, the best-fit model image, and the probability distributions for the MCMC posteriors are shown in Table 2, Figures 3(a) and (d), and Figure 9 in Appendix E, respectively. We subtracted modeled visibilities from observed visibilities (Figure 10 in Appendix F), and made a CLEANed image (Figure 3(e) in which we did not find significant residuals. To calculate the value of the reduced-\( \chi^2 \), we derived a factor between the weights and standard deviations (referred to as stddev) in the visibility measurements by calculating the standard deviations of the real and imaginary parts in \( 2 \lambda \) bins along the azimuthal direction in the visibility domain. The weights of values \( W_j \) are provided in the measurement set of ALMA data while the standard deviations (stddev) are calculated in our fitting. The visibilities were deprojected with \( i = 60^\circ \) and \( PA = 135^\circ \). Figure 11 in Appendix G shows a comparison between the weights and standard deviations (stddev). We found that the weights are typically \( 4.0 \times \) higher than the standard deviations. Finally, we calculated a reduced \( \chi^2 \) of 1.91. We also conducted visibility analyses using a model with one Gaussian ring + one asymmetry (i.e., \( \delta = 0 \)), and found significant residuals. Thus, the model with two Gaussian rings + one asymmetry is necessary to reproduce the observed dust continuum image.

Though the observed dust continuum image in Figure 1(a) shows two peaks along the ring major axis, our visibility analyses suggest that only the one at PA = 130° is real. The radial ring position (i.e., the peak position) and its FWHM (Ring A + Ring B) in the model image were measured to be 58 and 49 au in Figure 3(a). The contrast in the asymmetry, which is the ratio between the peak brightness at the asymmetry and that at its opposite side on the ring, is measured to be 3.0 in Figure 3(d).

5. Discussion

5.1. Azimuthal Asymmetry

Azimuthal asymmetries in rings have been identified in roughly 10 protoplanetary disks (e.g., van der Marel et al. 2021). At band 7, their shape parameters (e.g., the radial FWHM and the aspect ratio defined as the azimuthal FWHM divided by the radial FWHM) are summarized in Table 3.9 All

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7. Visibilities are deprojected in the uv-plane using the following equations (e.g., Zhang et al. 2016): \( u' = (\alpha \cos PA - v \sin PA) \times \cos i, v' = (\alpha \sin PA - v \cos PA) \), where \( i \) and PA are free parameters in our visibility analyses in Section 4.

8. https://casaguides.nrao.edu/index.php/DataWeightsAndCombination

9. The physical quantities of other asymmetries are taken from van der Marel et al. (2021). V1247 Ori shows a crescent structure in ALMA band 7 (Kraus et al. 2017). However, we do not include V1247 Ori because the structure does not have a Gaussian profile (Kraus et al. 2017). Though HD 142527 also shows a crescent structure in ALMA band 7 (Fukagawa et al. 2013), the visibility analyses in van der Marel et al. (2021) did not find convergence; thus, we do not include HD 142527.
but ZZ Tau IRS are intermediate mass stars (∼2 M☉). In Figure 4 we compare various properties of these asymmetries as a function of the peak radial location. Though ZZ Tau IRS is a VLM star, its asymmetry has similar properties to other asymmetries around more massive stars, implying a similar origin.

We explore the correlation in Figure 4 by calculating Pearson’s correlation coefficient r for logarithmic numbers except the aspect.

Figure 4. Comparison of the properties of the ZZ Tau IRS asymmetry with other asymmetries around intermediate mass stars as a function of the radial location. The red circle represents ZZ Tau IRS. The physical quantities and their brief explanations are summarized in Table 3. Pearson’s correlation coefficient r is inserted in the panels. The 5% significance values for Pearson’s r with n = 7 and 8 are 0.75 and 0.71, respectively (Pugh & Winslow 1966).
Figure 5. SED of ZZ Tau IRS without extinction correction. The photometric data are summarized in Table 4.

5.2. Gravitational Stability

ZZ Tau IRS’ disk is one of the most massive among VLM stars (see, Kurtovic et al. 2021). We examine its gravitational stability. Theoretical studies (e.g., Durisen et al. 2007) suggest that if the Toomre (1964) $Q$-parameter, defined as

$$Q = \frac{c_s \Omega_K}{\pi G \Sigma_{\text{disk}}}$$

where $c_s$, $\Omega_K$, and $\Sigma_{\text{disk}}$ are the sound speed, the Keplerian angular velocity, and the disk (gas) surface density, respectively, is of order of unity, the disk may be subject to gravitational instability (GI). With the scale height of $H \sim c_s/\Omega_K$, Toomre’s $Q$-parameter can be described as $Q \sim H/r \times M_{\text{star}}/M_{\text{disk}}$, where $M_{\text{disk}} = \pi r^2 \Sigma_{\text{disk}}$. Therefore, if the disk’s aspect ratio is $H/r \sim 0.1$, GI occurs in massive disks with $M_{\text{disk}}/M_{\text{star}} \gtrsim 0.1$. The disk-to-star mass ratio is $\sim 0.04–0.08$ in ZZ Tau IRS (Section 3.1), and thus the disk may be globally gravitationally stable. Meanwhile the $Q$-value at the asymmetry is $1.7–6.2$ assuming a local surface density $\Sigma_{\text{disk}} = \cos i \tau_i/\kappa_\nu = 7–20 \, \text{g/cm}^2$ ($i = 60^\circ$ and $\tau_i = 0.5–1.4$, Section 3.1), an opacity per unit dust mass of $\kappa_\nu = 3.45 \, \text{cm}^2 \, \text{g}^{-1}$ at 345 GHz Beckwith & Sargent (1991), a temperature of $17.8–28.6 \, \text{K}$ (Section 3.1), and a gas-to-dust mass ratio of 100. Hence, the asymmetry may also be marginally stable.

5.3. Possible Warped Inner Disk

ZZ Tau IRS has been suggested to have an edge-on inner disk (White & Hillenbrand 2004; Furlan et al. 2011), because the IR excess is larger than the optical stellar flux due to partial disk obscuration of the star (Figure 5 in the Appendix A). Our visibility analyses suggest that the outer ring at $r = 50 \, \text{au}$ has an inclination ($i$) of $60^\circ$ (Section 4). Radiative transfer calculations for protoplanetary disks (full disks) show that typically the central star starts to be significantly obscured by the disk once the inclination is larger than $\sim 70^\circ$ (e.g., see Figure 2 in Whitney et al. 2013). Hence ZZ Tau IRS could possess an inner disk misaligned with the outer ring. Such warped inner disks have been discovered in twisted gas flow patterns (e.g., Rosenfeld et al. 2014; Mayama et al. 2018) and shadows on the outer disk in NIR scattering images (e.g., Marino et al. 2015). For ZZ Tau IRS, current ALMA gas observations in Figure 2 are insufficient to confirm a twisted gas flow due to low spatial and spectral resolution. Furthermore, high spatial resolution observations of NIR scattering images have not yet been carried out. Another possible explanation of the observed SED is that the source is a “flat spectrum” young stellar object surrounded by an infalling dusty envelope (Calvet et al. 1994). In this case, an extended reflection nebula around the source is expected in NIR scattered light observations (e.g., similar to T Tau, Whitney & Hartmann 1993). Future observations are necessary to test these hypotheses.

A few possible mechanisms have been proposed to explain warped disks. An exciting one is disk–companion interactions (e.g., Zhu 2019), in which a massive companion with a companion-star mass ratio $q \gtrsim 0.01$ (or $M_p \gtrsim M_{J}$) around a $0.1M_\odot$ star) on an inclined orbit induces both a deep wide gap and a misaligned inner disk. Such a system with a massive companion and a misaligned inner disk has been reported in HD 142527 (Billot et al. 2012; Marino et al. 2015). Future detection of massive companions in the gap would serve as a test for the planet origin hypothesis.

Figure 5: SED of ZZ Tau IRS without extinction correction. The photometric data are summarized in Table 4.
6. Conclusion

We analyzed ALMA band 7 archive data (dust continuum and $^{12}$CO $J = 3 \rightarrow 2$ emission) of ZZ Tau IRS. The source has been classified as a VLM star with a mass of $\sim 0.1$–$0.2 M_\odot$ in the literature. The observed $^{12}$CO $J = 3 \rightarrow 2$ kinematics suggest a dynamical mass of $\sim 0.1$–$0.3 M_\odot$, consistent with previous estimates. The ALMA dust continuum image at a spatial resolution of 0″25 shows a ring and an asymmetric structure around ZZ Tau IRS. Our visibility analysis confirmed that the observed asymmetry is real rather than apparent.

Our best-fit model of the ALMA dust observations shows that the asymmetry has a radial FWHM of 11.3 au, an aspect ratio of 7:2 (ratio of azimuthal FWHM to azimuthal FWHM), and a brightness contrast of 3:0 and that the asymmetry contributes 5% of the total disk flux. These metrics are comparable with asymmetries seen around intermediate mass stars ($\sim 2 M_\odot$), implying a similar origin, despite ZZ Tau IRS being 10 times less massive. While future high spatial resolution observations in multiple wavelengths with ALMA and JVLA are needed to determine the exact origin of the asymmetry, the three leading hypotheses all invoke companions inside the gap.

The inner disk around ZZ Tau IRS, not visible in our observations, has been inferred to be edge-on based on the SED. Our observations showed that the inclination of the outer disk at $r = 50$ au is 60°. These results imply that the ZZ Tau IRS inner disk may be misaligned relative to the outer ring, and it is possible that the misalignment (and the gap) is produced by a giant planet with $M_p \gtrsim M_\oplus$ on an inclined orbit inside the gap. Future scattered light observations may test this hypothesis by searching for shadows on the outer disk cast by the inner disk.

Overall, the structures found in the ZZ Tau IRS disk suggest the presence of massive companions including gas giant planets at $\sim 10$ au. This is surprising as the core accretion theories have generally prohibited the formation of such planets around VLM stars (Liu et al. 2020; Miguel et al. 2020, Section 1). Hence, ZZ Tau IRS will be a prime target in the investigation of planet formation around VLM stars.

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**Software:** vis_sample (Loomis et al. 2017), CASA (McMullin et al. 2007), emcee (Foreman-Mackey et al. 2013).

**Appendix A**

SED of ZZ Tau IRS

Figure 5 shows the SED of ZZ Tau IRS. Extinction correction is not applied to show the large IR excess relative to the stellar flux. The photometric data without extinction correction are summarized in Table 4.

| Wavelength ($\mu$m) | $\Delta F_\lambda$ ($10^{-12}$ erg s$^{-1}$ cm$^{-2}$) | Reference       |
|-------------------|-----------------------------------------------|----------------|
| 0.44              | 1.25                                          | USNO-B1.0       |
| 0.64              | 20.5                                          | USNO-B1.0       |
| 0.80              | 16.1                                          | USNO-B1.0       |
| 1.23              | 28.3 ± 0.6                                    | 2MASS (Cutri et al. 2003) |
| 1.66              | 49.2 ± 1.0                                    | 2MASS (Cutri et al. 2003) |
| 2.16              | 69.4 ± 1.5                                    | 2MASS (Cutri et al. 2003) |
| 3.35              | 100.4 ± 2.0                                   | WISE (Cutri et al. 2014) |
| 4.60              | 164.5 ± 3.2                                   | WISE (Cutri et al. 2014) |
| 11.6              | 124.8 ± 1.6                                   | WISE (Cutri et al. 2014) |
| 22.1              | 193.8 ± 2.9                                   | WISE (Cutri et al. 2014) |
| 70                | 162.9 ± 34.3                                  | Herschel (Ribas et al. 2017) |
| 100               | 93.0 ± 18.0                                   | Herschel (Ribas et al. 2017) |
| 160               | 61.9 ± 13.1                                   | Herschel (Ribas et al. 2017) |
| 250               | 31.2 ± 6.0                                    | Herschel (Ribas et al. 2017) |
| 350               | 18.0 ± 3.4                                    | Herschel (Ribas et al. 2017) |
| 500               | 9.0 ± 1.8                                     | Herschel (Ribas et al. 2017) |
| 885               | 0.928 ± 0.093                                 | ALMA (this work) |
| 1300              | 0.244 ± 0.003                                 | SMA (Andrews et al. 2013) |

**Note.** Extinction correction is not applied here.
Appendix B
Dust Continuum Images Synthesized with Only the Imaginary Part

We shifted the observed dust continuum images to minimize the asymmetry relative to the phase center as follows. First, the proper motions of ZZ Tau IRS were calculated with the function `EPOCH_PROP` in GAIA ADQL (Astronomical Data Query Language\textsuperscript{10}). The phase centers were corrected to (4\textdegree30\textquoteright31.7346, +24\textdegree41\textquoteright47.175) in ICRS using `fixvis` in the CASA tools. Next, in order to make the analyses of the disk structure more effective, we further shift the center of the image by searching for the location where the disk asymmetry is minimized. We subtracted the 180°-rotated image in the visibility domain. This procedure corresponds to producing a synthesized image with only the imaginary part of the visibilities. This method has been utilized in the analyses of DM Tau (Hashimoto et al. 2021) and WW Cha (Kanagawa et al. 2021). Since the visibility $V$ is a Fourier transform of the surface brightness distribution of the sky, which is a real quantity, the visibility at $(-u, -v)$ in the $uv$-plane is a complex conjugate of that at $(u, v)$,

$$V(u, v) = V(-u, -v).$$ \hfill (B1)

The 180°-rotation of the image with respect to the origin $(x, y) = (0, 0)$ on sky corresponds to flipping the signs of both $(x, y)$ coordinates, i.e., $(x, y) \rightarrow (-x, -y)$. In the visibility domain, this is mathematically equivalent to flipping the signs of $(u, v)$. Therefore, the visibility of the 180°-rotated image is

$$V(u, v) \rightarrow V(-u, -v) = V(u, v).$$ \hfill (B2)

Thus, subtracting the 180°-rotated image is mathematically equivalent to setting the real part to zero and doubling the value.

![Figure 6. Dust continuum images synthesized with only the imaginary part of the long baseline data by shifting by 10 mas in the R.A. and decl. directions. The rms value is measured inside the black dotted circle with a diameter of 2\textdegree25. The 1σ noise is 0.268 mJy beam$^{-1}$ measured in a region far from the object. The beam size is 254 × 248 mas at a PA of −61.7°.](image)

\textsuperscript{10} https://gea.esac.esa.int/archive/
of the imaginary part as follows
\[ V(u, v) - V(-u, -v) = V(u, v) - V(-u, -v) = 2 \text{Im}(u, v). \]  
(B3)

In other words, the real part contains information on both the symmetric and asymmetric structures of objects, whereas the imaginary part contains only information on the asymmetries. Therefore, by synthesizing the image with only the imaginary part, we selectively remove symmetric structures and reveal only asymmetric structures. We determined the minimum rms in the central region of the images by shifting the images relative to the new GAIA phase center in the visibility domain by a phase shift of \[ \exp\left[ 2\pi i (\Delta \text{R.A.} \pm \Delta \text{decl.}) \right], \]
where \( u \) and \( v \) are the spatial frequencies and \( \Delta \text{R.A.} \) and \( \Delta \text{decl.} \) are the shift values. Figure 6 shows dust continuum images synthesized with only the imaginary part, including the image with the minimum rms. We found shift values for the minimum rms \( (\Delta \text{R.A.,} \Delta \text{decl.}) \) of \((-28 \text{ mas,} -23 \text{ mas}) \) relative to the phase center determined by GAIA. The final phase center in the ICRS coordinate is \((4^h30^m51.7325, +24^d41^m47.152)\).

**Appendix C**

\textbf{\(^{12}\text{CO} J = 3-2 \text{ Channel Maps}\)}

Figure 7 shows the \(^{12}\text{CO} J = 3 - 2\) channel maps at +1.0 to +13.0 km s\(^{-1}\).

![Channel maps of \(^{12}\text{CO} J = 3 - 2\) at different velocities.](image)

**Figure 7.** Channel maps of \(^{12}\text{CO} J = 3 - 2\). The rms noise at the 0.5 km s\(^{-1}\) bin is 9.56 mJy beam\(^{-1}\) with a beam size of 283 × 156 mas at a PA of −50°2.
Appendix D

Trace Plots in MCMC Calculations

Figure 8 shows trace plots for 100 walkers for 13 parameters in the model in our visibility analyses (Section 4). The burn-in phase is set as the initial 1000 steps.

Figure 8. Trace plots for 100 walkers for 13 parameters in the model. The initial 1000 steps are set as the burn-in phase and are discarded in the histograms of the marginal distributions of the MCMC posteriors in Figure 9.
Appendix E
Histogram of the Marginal Distributions for the MCMC Posteriors

Figure 9 shows a corner plot of the MCMC posteriors calculated in visibility analyses in Section 4.

Figure 9. Corner plot of the MCMC posteriors calculated in visibility analyses in Section 4. The histograms on the diagonal are marginal distributions of 13 free parameters. The parameter ranges in each parameter are described in Table 2. The vertical dashed lines in the histograms represent the median values and the 1σ confidence intervals for parameters computed from the 16th and 84th percentiles. The off-diagonal plots show the correlation for corresponding pairs of parameters.
Appendix F
Observed and Modeled Visibilities

Figure 10 shows observed and modeled visibilities in our visibility analyses (Section 4).

![Figure 10](image)

*Figure 10. Real (a) and imaginary (b) parts of the visibilities for the observations (red dots) and the best-fit model (black line) in the top panel in visibility analyses in Section 4. The bottom panel shows residual visibilities between observations and the best-fit model. The reduced-$\chi^2$ is 1.91.*

Appendix G
Weight Values and Standard Deviations in the Real and Imaginary Parts

Figure 11 shows a comparison of the values of weights and standard deviations in the real and imaginary parts. The values

![Figure 11](image)

*Figure 11. Comparison of weights and standard deviations (stddev) in real and imaginary parts. The weights are typically 4.0× higher than $1/\text{stddev}^2$ of the real and imaginary parts at 100–600 $k\lambda$.***
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