Substructure Formation in a Protostellar Disk of L1527 IRS

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Received 2019 December 29; revised 2020 April 28; accepted 2020 April 29; published 2020 May 15

Abstract

We analyze multifrequency, high-resolution continuum data obtained by the Atacama Large Millimeter/submillimeter Array and the Jansky Very Lary Array to study the detailed structure of the dust distribution in the infant disk of a Class 0/I source, L1527 IRS. We find three clumps aligning in the north–south direction in the 7 mm radio continuum image. The three clumps remain even after subtracting free–free contamination, which is estimated from the 1.3 cm continuum observations. The northern and southern clumps are located at a distance of ∼15 au from the central clump and are likely optically thick at 7 mm wavelength. The clumps have similar integrated intensities. The symmetric physical properties could be realized when a dust ring, or spiral arms, around the central protostar is projected to the plane of the sky. We demonstrate for the first time that such substructure may form even in the disk-forming stage, where the surrounding materials actively accrete toward a disk-protostar system.

Unified Astronomy Thesaurus concepts: Interstellar medium (847); Protostars (1302); Young stellar objects (1834); Circumstellar dust (236); Dust continuum emission (412); Star formation (1569); Planetary system formation (1257)

1. Introduction

Since dust is the building block of planets, its spatial distribution is considered to directly link to the birthplaces of planets. Recent millimeter observations have revealed substructures in protoplanetary disks, such as rings, gaps, and spirals. Substructures are found in all 20 Class II targets in the Disk Substructures at High Angular Resolution Project (e.g., Andrews et al. 2018). The results suggest that substructures are likely common among protoplanetary disks. Investigating the origin is thus essential in the context of planet formation.

Theoretical works have proposed several mechanisms that can be responsible for the substructures: torques due to massive planets (e.g., Goldreich & Tremaine 1980), secular gravitational instability (e.g., Youdin 2011), dust sintering (e.g., Okuzumi et al. 2016), etc., but a consensus has yet to be reached. The verification requires observations to constrain when the substructure formation begins and how large dust has grown by that time. To this end, investigating dust distribution is necessary for younger sources with multiwavelength observations. Recent continuum observations by the Atacama Large Millimeter/submillimeter Array (ALMA) have detected ring structures in the disks around Class I protostars (Sheehan & Eisner 2017, 2018). However, it is not yet known if substructures can also form in even younger systems.

The protostellar core L1527 is known to harbor a Class 0/I protostar, IRAS 04368+2557. It has been reported that a rotationally supported disk exists (Tobin et al. 2013; Ohashi et al. 2014; Sakai et al. 2014; Aso et al. 2017). The disk size is \( \sim 80 \) au (Oya et al. 2016, 2018), which is common among Class 0 sources (Yen et al. 2015), while the relatively short distance of 137 pc (Torres et al. 2007) makes it an optimal target to study substructure formation.\(^6\) The envelope-disk system of L1527 IRS is nearly edge-on with the disk slightly warped at 40–60 au (Sakai et al. 2019). In this study, the inner part of the warped disk (\( r < 50 \) au) is resolved by multiwavelength observations with ALMA (Band 7, Band 4, and Band 3) and the Jansky Very Lary Array (JVLA; Q band and K band).

2. Observations

2.1. ALMA Observations

In the millimeter-wavelength range, we use ALMA to observe the disk around the protostar, IRAS 04368+2557. The observations have been carried out from 2015 to 2017. The observation summary is presented in Tables A1 and A2. The pointing and phase referencing centers were on R.A. = 04h39m53s±870 (J2000), decl. = +26°03′09″6 (J2000). We use the Astronomy Software Applications (CASA; McMullin et al. 2007) package for the calibration and analysis. The reduction and calibration are done with CASA in a standard manner.

The proper motion of the target source is appreciable (\( \mu_\alpha = 0.5 \) mas yr\(^{-1}\), \( \mu_\delta = -19.5 \) mas yr\(^{-1}\); Loinard et al. 2002). To allow joint imaging of all data, and to compare the observations, we used the CASA task FIXPLANE to shift the target source to the expected coordinates on 2017 August 1. (See Appendix A for the more details.)

2.2. JVLA Observations

We have retrieved the archival National Radio Astronomical Observatory (NRAO) Karl G. JVLA observations toward L1527 IRS. The pointing and phase referencing centers were on R.A. = 04h39m56s±600 (J2000), decl. = +26°03′06″0 (J2000). They were carried out from 2011 to 2013, which were interleaved with Q band, K band, and C band.

Notes:

1. Note that Tobin et al. (2020) have reported an average radius of ∼45 au for Class 0 disks in the Orion molecular clouds.
observations in each epoch. The observations utilized the standard continuum observing modes, which took full RR, RL, LR, and LL correlator products over a \(\sim 2\) GHz bandwidth coverage in 2011 using the 8 bit sampler, and over a \(\sim 8\) GHz bandwidth coverage using the 3 bit sampler in 2013. The observations in 2011 adopted a 1 s integration time, while the observations in 2013 adopted a 3 s integration time. Table A1 in Appendix A summarizes the details of these observations. We give a summary of the JVLA observations in Tables A1 and A2.

We manually calibrated the data following the standard calibration procedure, using the CASA (McMullin et al. 2007) package (release 4.7.2). The proper motion of the target source is also taken into account. (See Section 2.1.) We combined A and B configuration data of Q-band observation to obtain the map shown below. The map for each configuration data is also shown in Appendix A.2. It also describes our data calibration in detail. Note that the data at \(uv\) distances greater than 1000 \(k\lambda\) was flagged for Q-band.

3. Results

3.1. Observed Images

Figure 1 shows the intensity maps at ALMA Band 7, and JVLA Q- and K-bands, respectively. The color map represents the brightness temperature. The horizontal and vertical axes indicate west–east and south–north directions. The white ellipses at the bottom left indicate the beam sizes (\(\theta_{\text{maj}} \times \theta_{\text{min}}\) P.A.): \(0.072 \times 0.067; -11^\circ\) (Band 7), \(0.087 \times 0.068; 76^\circ\) (Q band), and \(0.095 \times 0.075; -82^\circ\) (K band). The rms noise level is 0.3 K, 11 K, and 21 K for Band 7, Q band, and K band, respectively. In the ALMA Band 7 image, the green contours show the brightness temperature; the first contour starts at 10\(\sigma\), and the interval is 23\(\sigma\). The clump locations are marked with the crosses. For the JVLA images, the green contours show the brightness temperature observed at Q band; the first contour is at 3.5\(\sigma\) (\(\sim 40\) K), and the interval is 3.0\(\sigma\). The blue dashed line indicates the midplane, which we define as the north–south line passing through the peak position of clump-N in the subtracted image.

Figure 1. (a)–(c) Intensity maps for the observed data at ALMA Band 7, and JVLA Q- and K-bands, respectively. The color map represents the brightness temperature. The horizontal and vertical axes indicate west–east and south–north directions. The white ellipses at the bottom left indicate the beam sizes (\(\theta_{\text{maj}} \times \theta_{\text{min}}\) P.A.): \(0.072 \times 0.067; -11^\circ\) (Band 7), \(0.087 \times 0.068; 76^\circ\) (Q band), and \(0.095 \times 0.075; -82^\circ\) (K band). The rms noise level is 0.3 K, 11 K, and 21 K for Band 7, Q band, and K band, respectively. In the ALMA Band 7 image, the green contours show the brightness temperature; the first contour starts at 10\(\sigma\), and the interval is 23\(\sigma\). The clump locations are marked with the crosses. For the JVLA images, the green contours show the brightness temperature observed at Q band; the first contour is at 3.5\(\sigma\) (\(\sim 40\) K), and the interval is 3.0\(\sigma\). (d) The bottom right panel shows the Q band image where free–free contamination is subtracted. The beam size is \(0.096 \times 0.076; -82^\circ\). The solid blue contours in the subtracted map are plotted in the same manner as (b) and (c), but with 1.5\(\sigma\) intervals and the rms noise level in the smoothed Q band data, \(\sigma' \sim 7\) K. The estimated free–free emission for Q band is indicated by the green dashed contours at 2, 3, 4, and 5\(\sigma'\). The blue dashed line indicates the midplane, which we define as the north–south line passing through the peak position of clump-N in the subtracted image.
both A- and B-con
features of the detected clumps in our actual observations with
the north in Figure C2. Figure A2 shows an example of our synthetic observations for a smooth disk observations even with an hour integration time. The Astrophysical Journal Letters, of the disk is VLA B-con
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∂/∂ + ∂/∂ = 0 above the midplane between the lowest two bands (Figure 2). It is consistent with that expected for an optically thin free–free emission from a thermal plasma protruding westward from the protostar. The spectral index is close to ∼2 at clump-C, where the emission is likely optically thick. The apparent offset between the K-band peak and clump-C may originate from the difference in the optical depth. This offset has been consistently resolved in multiepoch observations with different array configurations (Figure A2), and our calibrator fluxes are sufficiently accurate (Table A1 in Appendix A). It suggests the offset to be physical.

The C band observations have too poor angular resolution (∼0.04") to confirm the angular offset. In addition, we are not able to unambiguously determine the spectral index, because we cannot constrain the parameters of free–free emission (e.g., density, temperature, and emission measure) without degeneracy with the currently available data. Still, the estimated

\begin{equation}
\alpha_{\lambda_1-\lambda_2} = \frac{\ln I_1 - \ln I_2}{\ln \nu_1 - \ln \nu_2},
\end{equation}

where \( \lambda_1, I_1, \) and \( \nu_1 \) denote the wavelength, intensity, and frequency at the \( i \)th band: Band 7 (0.9 mm), Band 4 (2 mm), Band 3 (3 mm), \( Q \) band (7 mm), and \( K \) band (1.3 cm). To derive \( \alpha \), we smooth the two images by the minimum beam that covers the beams of the original two data, and we use data with 3σ or higher detection.

We find that the spectral indices between the ALMA data and the \( Q \) band data show \( \alpha \) \( \lesssim 2 \) for the <20 au region, being consistent with optically thick dust emission (see Appendix B for more details).

Typical spectral index is \( \alpha \) \( _{7\text{mm} - 1.3\text{cm}} \sim 0 \) above the midplane between the lowest two bands (Figure 2). It is consistent with that expected for an optically thin free–free emission from a thermal plasma protruding westward from the protostar. The spectral index is close to ∼2 at clump-C, where the emission is likely optically thick. The apparent offset between the K-band peak and clump-C may originate from the difference in the optical depth. This offset has been consistently resolved in multiepoch observations with different array configurations (Figure A2), and our calibrator fluxes are sufficiently accurate (Table A1 in Appendix A). It suggests the offset to be physical.

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Figure 2. Map of the \( \alpha \) index derived with the observation data at \( K \) and \( Q \) bands. The synthesized beam size is shown at the bottom left, and the size is \( 0''096 \times 0''076; -82^{\circ}. \) The red contours are shown in the same manner as Figure 1.
spectral index alpha between K and C band data ($\sim$0.4–0.7) is consistent with optically thin free–free emission at the K band. Note that free–free emission can be optically thick at the C-band frequencies. The peak may indicate a current shock position or originate from a highly opaque central region that attenuates the free–free emission from the other half of the H II region. Note that the disk inclines by $i \sim 5$ deg; the western disk surface faces us (Tobin et al. 2008, 2010; Oya et al. 2015; Aso et al. 2017).

The $\alpha$ maps suggest that we observe optically thick dust emission in the ALMA images and observe dust emission contaminated by free–free emission in the $Q$-band image. To extract free–free contamination from the $Q$-band data, we smooth the $Q$ and $K$ band images with the minimum beam that covers both of the $K$- and $Q$-band beams to subtract the free–free contamination as

$$I_{\text{7 mm, dust}} = I_{\text{7 mm}} - I_{\text{1.3 cm}} \left( \frac{\nu_{\text{7 mm}}}{\nu_{\text{1.3 cm}}} \right)^{-0.1},$$

where the adopted spectral index, $-0.1$, is typical for optically thin free–free emission (e.g., Anglada et al. 2018) and is consistent with the aforementioned measurements of $\alpha_{\text{7 mm–1.3 cm}}$. The three clumps are evident in the subtracted intensity map regardless of a larger beam size than that of the original $Q$-band image (Figure 1(d)). Both clump-N and -S are located at a distance of $\sim 15$ au from clump-C. The brightness temperatures are similar ($\approx 60$ K) for all the clumps. The clump-C temperature may be underestimated because Equation (2) likely overestimates the contamination at the clump-C position (see Figure 2).

4. Discussions

The clumpy structure shown in the $Q$-band image can be indicative of substructure in L1527 IRS. In this section, the physical properties of the clumps are examined to consider the actual clump geometry and possible origins. We first present our measurements of the optical thickness (Section 4.1) and the mass (Section 4.2), then discuss the geometry and origins (Section 4.3).

4.1. Optical Thickness

We adopt the opacity model of Birnstiel et al. (2018) in our discussions. Given that we have not detected evidence of dust growth in the system and this is also the case for Class II disks (e.g., Kataoka et al. 2016; Liu 2019), we assume $a_{\text{max}} \lesssim 100$ $\mu$m in the following discussions.\footnote{Scattering opacity is negligible for $a_{\text{max}} \lesssim 100$ $\mu$m, while it dominates over absorption opacity for $a_{\text{max}} \gtrsim 400$ $\mu$m.} Using the temperature model of Tobin et al. (2013), we estimate $\tau_{\text{7 mm}}$ along the midplane as

$$\tau_{\text{7 mm}} = -\ln \left( 1 - \frac{T_{\text{7 mm}}}{T_{\text{model}}} \right),$$

where $T_{\text{model}}$ is the model temperature. The model temperature is extremely high around clump-C, which can lead to a significant underestimation of $\tau_{\text{7 mm}}$. To approximately account for the possible distance between clump-C and the protostar, we also use a modified temperature distribution, $T'_{\text{model}}$, by truncating $T_{\text{model}}$ from the top within 5 au, which corresponds to the Gaussian-fit scale of clump-C. The resulting $\tau_{\text{7 mm}}$ is shown in Figure 3. The regions around clump-N and -S appear to be optically thick ($\tau_{\text{7 mm}} > 1$); the gap regions ($d \lesssim 15$ au) are marginally optically thick $\tau_{\text{7 mm}} \sim 1$, and the outer ($d \gtrsim 20$ au) regions are optically thin $\tau_{\text{7 mm}} < 1$.

We have found $\alpha$ values of $\alpha_{\text{3 mm–7 mm}}$ ($\approx 2.5–2.8$) at $d = 30$ au and $\alpha_{\text{0.9 mm–3 mm}}$ ($\approx 2–2.5$) at $d = 40$ au (see Figure B1). The $\alpha$ values are much smaller than the typical interstellar value ($\alpha \approx 3.8$; Draine 2006). This could suggest dust growth from the interstellar dust at the outer region of L1527 IRS’s inner disk ($\gtrsim 30–40$ au).

4.2. Clump Masses

We estimate the dust mass at clump-N and -S as

$$M_{\text{dust}} = 0.59 M_\odot \left( \frac{\kappa_{\text{7 mm}}}{0.02 \text{ cm}^2 \text{ g}^{-1}} \right)^{-1} \times \int_A \frac{dA}{(10 \text{ au})^2} \ln \left( 1 - \frac{I_{\text{7 mm}}}{B_{\text{7 mm}}(T_{\text{model}})} \right),$$

where $A$ is an integration area, $B_\nu$ is the Planck function, and $\kappa_{\text{7 mm}}$ is the absorption opacity at the $Q$ band. Note that the absorption opacity is $\approx 0.02 \text{ cm}^2 \text{ g}^{-1}$ for $a_{\text{max}} \lesssim 100$ $\mu$m (Birnstiel et al. 2018). Since the clumps are not resolved, we set $A$ to the synthesized beam size whose center is located at the peak of each clump. Adopting $\kappa_{\text{7 mm}} = 0.02 \text{ cm}^2 \text{ g}^{-1}$, we estimate the lower limits of the clump mass to be 0.40 $M_\odot$ for clump-N and 0.48 $M_\odot$ for clump-S. The lower limit of the total dust mass (with 3$\sigma$ or higher detection) is 2.7 $M_\odot$.
The total dust mass corresponds to the total disk mass of $M_{\text{disk}} \sim 0.26 M_\odot$ for dust-to-gas mass ratios of 1%, which implies that the disk mass accounts for a large fraction (\sim 50–100%) of the system’s mass estimated from the rotation curve of \sim 1 mm observations in prior studies (\sim 0.2–0.46 $M_\odot$; Ohashi et al. 2014; Sakai et al. 2014; Aso et al. 2017). The inner disk has turned out to be likely optically thick at the band in this study, and thus its contribution to the system mass could have been underestimated.

An important note is that our estimated mass suffers from huge uncertainties mainly originating from a poor understanding of dust opacity at centimeter-wavelengths. The adopted dust opacity may be low, leading us to obtain a high mass for the clumps and disk. The opacity model of Woitke et al. (2016) predicts about an order of magnitude larger absorption opacity than the adopted one in this study. (However, scattering dominates at centimeter-wavelengths in their model) In addition, the dust-to-gas mass ratio is also uncertain. We stress that the estimated mass works as no more than a reference. Future observations and models are indispensable for an accurate mass measurement. Nevertheless, we show our measurement results, expecting it to be a reference for future studies.

4.3. Clump Geometry and Origins

The previous 7 mm VLA observations of Loinard et al. (2002) have detected the disk as an elongated component with the data sets obtained on 1996 December 31 and 2002 April 10. The extension of the disk is largely similar to those of clump-N and -S,\(^8\) which implies that the projected distances remain the same for about 20 yr. The symmetries in the locations, mass, and time of clump-N and -S may indicate consistency with an axisymmetric geometry rather than individual chunks. Note that clump-N is not as bright as clump-S or clump-C (Figures A2 and C1). Possibilities of being individual chunks are not ruled out.

If the Q-band data shows an axisymmetric structure, a dust ring and symmetric spiral arms are plausible candidates. We derive the Toomre parameter (Toomre 1964) by approximately estimating surface density as $\Sigma \approx 100 M_{\text{dust}}(<d)/\pi d^2$ (see Equation (4)). The $Q$-values are much lower than unity for \sim 15 au such that the disk causes significant fragmentation if the equation of state (EOS) is approximated to be isothermal. Emission would not be observed as a disk for a long period of time if this is the case. It could indicate errors in our mass measurements or that the substructure is actually individual clumps. In any case, there are uncertainties in our mass measurements, and thus disk stability would be a matter of discussion after an accurate measurement is conducted with high S/N data obtained by future observations. Besides, validating isothermal EOS would not be trivial in strongly accreting systems as L1527 IRS. Note that although the disk-to-star mass ratio is estimated to be high, such disks do not necessarily fragment (Kratter et al. 2010).

The observed clumps are consistent with a projected dust ring if the disk is stable or marginally gravitationally unstable, leaving the origins as an open question. Dust sintering is possible to form a dust ring (Okuzumi et al. 2016; Okuzumi & Tazaki 2019). Interestingly, our small $\alpha$ values ($\sim 2.5$) at $d \gtrsim 30–40$ au and nearly identical locations of the clumps to CO$_2$ snow line (Figure 3) are compatible with this scenario. Secular gravitational instability (SGI; Youdin 2011; Takahashi & Inutsuka 2014) is another possible explanation for a dust ring. Since L1527 IRS is an infall-dominant source, the age would be $\sim 10^4–10^5$ yr, which is comparable to the typical growth timescale of SGI.

For further investigation, we need gas kinematics observations with <30 au resolution and continuum observations at longer wavelengths with high angular resolutions to examine dust growth in the gap regions.

5. Summary

We analyze high-resolution dust continuum data of L1527 IRS obtained by ALMA (Bands 3, 4, and 7) and JVLA (Q, K, and C bands). We have found three clumps aligning north to south in the Q-band data. The clumps are consistently detected in independent multiepoch observations with different array configurations over a period of 2 yr. We have concluded that the clumpy structure has a physical origin and is indicative of substructure in L1527 IRS. The north and south clumps are symmetrically located at a distance of \sim 15 au with respect to the central clump and are likely optically thick. The integrated intensities are also similar. The symmetric characters propose a symmetric geometry such as a dust ring and symmetric spiral arms. However, considering less brightness of the northern clump compared to the southern clump, possibilities of being independent clumps are not ruled out. The origins of the substructure remain unclear. Observing gas kinematics and dust continuum at lower-frequency bands is essential to address the issue. Most importantly, our results demonstrate that substructure formation can occur at the earliest stage of protostellar disk system formation.

We thank Satoshi Okuzumi, Hiroshi Kobayashi, Sanemichi Takahashi, and Hideko Nomura for fruitful discussions. We are also grateful to the anonymous referee for giving us practical and insightful comments, which have greatly improved this manuscript. R.N. is supported by the Special Postdoctoral Researchers (SPDR) Program at RIKEN and by Grant-in-Aid for Research Activity Start-up (19K23469).

H.B.L. is supported by the Ministry of Science and Technology (MoST) of Taiwan (grant Nos. 108-2112-M-001-002-MY3). S.O. is supported by SPDR Program and JSPS KAKENHI grant No. 18K13595. Y.Z. is supported by SPDR Program and JSPS KAKENHI grant No. JP19K14774. N.S. is supported by Grant-in-Aid for Scientific Research (S) grant No. 18H05222. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This paper makes use of the following ALMA data: ADS/JAO.ALMA\#2016.1.01203.S, ADS/JAO.ALMA\#2017.1.00509.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/NSF, and NAOJ.

Facilities: JVLA, ALMA.

Software: CASA (McMullin et al. 2007).

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\(^8\) Loinard et al. (2002) also found an additional unresolved blob to the east of the disk, which has not been confirmed by other observations, including ours.
Appendix A
Observation Summaries

A.1. ALMA

The two epochs of observations shared an identical spectral setup, which provided five spectral windows at [146.965, 150.494, 150.432, 138.175, 138.346] GHz central frequencies with [58.594, 58.594, 58.594, 58.594 937.500] MHz frequency widths and [15.259, 30.518, 30.518, 15.259, 488.281] kHz frequency channel widths.

The observations of Epoch 1 were calibrated using the CASA (McMullin et al. 2007) package (release 4.7.0) and with Pipeline-Cycle4-R2-B. The gain calibrator selected for Epoch 2 was faint, such that the standard pipeline failed to produce usable calibrated visibilities. We manually calibrated the observations of Epoch 2 using the 5.4.0 release of CASA. After implementing the antenna position corrections, water vapor radiometer solution, and system temperature table, we performed the passband calibrations. To yield reasonably high S/Ns when deriving the gain phase solutions, we first solved the phase offsets among spectral windows using the passband calibration scan. After applying the passband and phase offset solution, we then derived the gain phase and amplitude solutions by combining all spectral windows. We derived the absolute flux scaling factors for the individual five spectral windows by querying the fluxes of the calibrator J0510 +1800 from the calibrator grid monitoring survey of ALMA. Finally, we performed three iterations of gain phase self-calibration using the spectral window which has the broadest frequency width, and then applied the solutions to all five spectral windows. The ALMA observations are summarized in Table A1. We show Band 7 image in Figure 1, and Bands 4 and 3 images in Figure A1. Table A2 provides the image properties.

A.2. JVLA

We split the Q, K, and C band data from individual epochs of observations before calibrating them separately. Following the standard procedure, we first implemented the corrections for antenna positions, the weather information, the gain-elevation curve, and the opacity model to all data. Afterwards, we performed per-integration gain phase calibration for the absolute flux and passband calibrators, and then bootstrapped the delay fitting and passband calibration by referencing the absolute flux from quasar 3C 147. We adopted the Perley–Butler 2010 and Perley–Butler 2013 flux standards (Perley & Butler 2013) for the observations taken before and after 2012, respectively. After applying the delay and passband solutions, we derived the per-integration gain phase solutions for all calibrators, and derived the per-scan complex gain solutions for the gain calibrator. We applied the per-integration gain phase solution when deriving the per-scan gain amplitude solutions for all calibrators, and then derived the absolute flux calibration factors based on the per-scan gain amplitude solutions by referencing to the aforementioned 3C 147 flux standards. Finally, we applied the delay, passband, per-scan gain amplitude solution, per-scan gain phase solution, and the absolute flux calibration factors to the observations on our target source.

Owing to that the target source is not bright enough to be eligible for gain phase self-calibration, careful and extensive data flagging was performed, in particular, for the A array configuration observations taken in the summer of 2011, to ensure that the final images were not significantly distorted or unsharpened due to phase error and dispersion. More specifically, we flagged the Q band (44–46 GHz) data, which were taken in 2011 at below 35° elevation, and flagged the Q band data taken on 2011 August 6 which were taken with the >1000 kλ projected baselines. As a consequence, all 44–46 GHz data taken on 2011 July 21 were flagged.

We performed the multifrequency synthesis imaging using the CASA task TCLEAN, by setting the parameter nterm = 1. Figure A2 shows the images generated from all data, all A array configuration (only) data, all B array configuration (only) data, all A array configuration (only) data, all B array configuration (only) data.

Figure A1. Brightness temperature maps for ALMA Band 4 and Band 3 observations. The beam sizes are 0″195 × 0″133, 5″2 and 0″155 × 0″068, 1″6, and the rms noises are 0.3 K for both Bands 4 and 3, respectively. The green contours are shown in the same manner as the ALMA Band 7 image in Figure 1, but the interval is 25σ and 65σ for the Bands 4 and 3 images, respectively.
| Track ID (#) | Band       | Observing Date UTC (YYYY MM DD) | Array Config. | Freq. Coverage (GHz) | Projected Baseline Lengths (m) | Flux/Passband Calib. | Phase Calib. | Gain Calib. Flux (Jy) | Obs. ID |
|-------------|------------|---------------------------------|---------------|----------------------|---------------------------------|----------------------|--------------|------------------------|---------|
|             | JVLA-C band | 2011 Jul 21                     | A             | 4.1–7.8              | 320–31800                     | 3C 147               | J0431+2037   | 2.7 ± 0.002             | evla/pdb/4128974 |
|             | JVLA-K band | 2011 Jul 21                     | A             | 22–24                | 740–28150                     | J0431+2037           | 0.68 ± 0.00065 | 0.35 ± 0.002             | (PI: Melis) |
|             | JVLA-Q band | 2011 Jul 21                     | A             | 44–46                | 680–26980                     | J0438+3004           | 0.35 ± 0.002 | 0.35 ± 0.002             | (PI: Melis) |
|             | JVLA-C band | 2011 Jul 24                     | A             | 4.1–7.8              | 350–31840                     | 3C 147               | J0431+2037   | 2.7 ± 0.002             | evla/pdb/4128974 |
|             | JVLA-K band | 2011 Jul 24                     | A             | 22–24                | 750–30100                     | J0431+2037           | 0.64 ± 0.00065 | 0.36 ± 0.001             | (PI: Melis) |
|             | JVLA-Q band | 2011 Jul 24                     | A             | 44–46                | 740–31320                     | J0438+3004           | 0.36 ± 0.001 | 0.36 ± 0.001             | (PI: Melis) |
|             | JVLA-C band | 2011 Aug 6                      | A             | 4.1–7.8              | 660–35690                     | 3C 147               | J0431+2037   | 2.7 ± 0.003             | evla/pdb/4128974 |
|             | JVLA-K band | 2011 Aug 6                      | A             | 22–24                | 930–33950                     | J0431+2037           | 0.70 ± 0.0013 | 0.40 ± 0.001             | (PI: Melis) |
|             | JVLA-Q band | 2011 Aug 6                      | A             | 44–46                | 960–35200                     | J0438+3004           | 0.40 ± 0.001 | 0.40 ± 0.001             | (PI: Melis) |
|             | JVLA-C band | 2013 Oct 4                      | B             | 4.1–7.8              | 220–10910                     | 3C 147               | J0403+2600   | 2.6 ± 0.003             | evla/pdb/21340702 |
|             | JVLA-K band | 2013 Oct 4                      | B             | 18–26                | 200–9380                      | J0403+2600           | 1.2 ± 0.00065 | 0.17 ± 0.003             | (PI: Melis) |
|             | JVLA-Q band | 2013 Oct 4                      | B             | 40–48                | 210–10510                     | J0440+2728           | 0.17 ± 0.003 | 0.17 ± 0.003             | (PI: Melis) |
|             | JVLA-C band | 2013 Oct 19                     | B             | 4.1–7.8              | 160–10080                     | 3C 147               | J0403+2600   | 2.6 ± 0.004             | evla/pdb/21340702 |
|             | JVLA-K band | 2013 Oct 19                     | B             | 19–26                | 200–9380                      | J0403+2600           | 1.1 ± 0.00052 | 0.16 ± 0.0005             | (PI: Melis) |
|             | JVLA-Q band | 2013 Oct 19                     | B             | 40–48                | 170–9930                      | J0440+2728           | 0.16 ± 0.0005 | 0.16 ± 0.0005             | (PI: Melis) |
|             | JVLA-C band | 2013 Nov 10                     | B             | 4.1–7.8              | 140–10240                     | 3C 147               | J0403+2600   | 2.6 ± 0.003             | evla/pdb/21340702 |
|             | JVLA-K band | 2013 Nov 10                     | B             | 18–26                | 150–9250                      | J0403+2600           | 0.99 ± 0.00085 | 0.15 ± 0.0002             | (PI: Melis) |
|             | JVLA-Q band | 2013 Nov 10                     | B             | 40–48                | 160–9280                      | J0440+2728           | 0.15 ± 0.0002 | 0.15 ± 0.0002             | (PI: Melis) |
|             | ALMA-Band 3 | 2017 Nov 13                     | C43-8          | 85–100               | 113–13900                     | J0510+1800           | J0435+2532   | 0.90 ± 0.0006            | A001/X1220/X5d2  |
|             | ALMA-Band 3 | 2017 Nov 14                     | C43-8          | 85–100               | 113–12300                     | J0510+1800           | J0435+2532   | 0.91 ± 0.0005            | A001/X1220/X5d2  |
|             | ALMA-Band 4 | 2016 Nov 19                     | C40-4          | 138–150              | 15–704                        | J0510+1800           | J0438+3004   | 0.35 ± 0.003             | A001/X5ac/Xe4a  |
|             | ALMA-Band 4 | 2017 Sep 3                      | C40-7          | 138–151              | 21–3700                       | J0510+1800           | J0440+2728   | 0.11 ± 0.006             | A001/X5ac/Xe4a  |
|             | ALMA-Band 7 | 2015 Jul 18                     | C34-7(6)       | 338–352              | 42–1574                       | J0423–013/J0423–0120 | J0438+3004   | 0.12 ± 0.004             | A001/X10f/X868  |
|             | ALMA-Band 7 | 2017 Jul 29                     | C40-5          | 17–1100              | 168–6800                      | J0510+1800           | J0438+2728   | 0.42 ± 0.04              | A001/X8aa/X23   |
|             | ALMA-Band 7 | 2017 Jul 29                     | C40-8          | 17–1100              | 168–6800                      | J0510+1800           | J0438+3004   | 0.20 ± 0.005             | (PI: Sakai)    |

Note. The gain calibrators flux for ALMA Bands 3, 4, and 7 are taken at 87 GHz (1.875 GHz bandwidth), 150.4 GHz (58.59 MHz bandwidth), and 345.8 GHz, respectively. The errors of the gain calibrator flux show statistical uncertainties but absolute flux uncertainties.
data, and from the individual three tracks of the B array configuration observations. The weighing scheme and the yielded synthesized beam sizes and rms noise levels of these images are summarized in Table A2 in Appendix A. In spite of the different synthesized beam shapes, these images consistently present an elongated (north–south) geometry, which appears clumpy and lopsided. We recovered a $\sim 3.7$ mJy total flux density at the mean frequency of $\sim 45$ GHz, which is very consistent with the $3.5$ mJy flux density (at 43 GHz) reported by Li et al. (2017), which was derived from the historical VLA observations taken in 1996–2004 (see Loinard et al. 2002; Melis et al. 2011).

Figure A2. JVLA 22–24 GHz (K band) and 44–46 GHz (Q band) images generated with various combinations of array configuration(s). These images are primary beam corrected. The details of these image are summarized in Table A2. B1, B2, and B3 refers to Tracks 4, 5, and 6, respectively.
Appendix B
Spectral Index $\alpha$ and Dust Growth

We derive $\alpha$ with the highest-resolution data: Band 7, Band 3, and $Q$ band (Figure B1). The values of $\alpha_{3\text{ mm}-7\text{ mm}}$ are $\sim2.49^{+0.66}_{-0.51}$ and $2.77^{+0.54}_{-0.54}$ at $d = 30$ au to the north and to the south, respectively, where $d$ is the distance from clump-C. The derived value is consistent with that previously reported for Band 7 and Band 6 ($1.3$ mm), $\alpha_{0.7\text{ mm}-1.3\text{ mm}} \sim 2.7$ (Sakai et al. 2019).

The profile of $\alpha_{0.9\text{ mm}-3\text{ mm}}$ is symmetric with respect to the center. The typical value is $\alpha_{0.9\text{ mm}-3\text{ mm}} = 2.5$ at $d = 40$ au and decreases toward the center. It reaches $\alpha_{0.9\text{ mm}-3\text{ mm}} = 2$ at $d = 30$ au. The value of $\alpha_{0.9\text{ mm}-3\text{ mm}}$ is apparently small ($<2$) for $d < 30$ au, which results from the lower brightness temperature at Band 7 than at Band 3.

One possible explanation for the anomalously low $\alpha$ is observing different radii at various frequencies (Li et al. 2017; Galván-Madrid et al. 2018). Since opacities are larger for shorter wavelengths, hot dust layers can be obscured by foreground dust at larger radii in our edge-on disk. Lower temperatures are expected for shorter-wavelength bands in this case. The Band 4 image shows $T_b$ nearly equal to that at Band 7 despite the relatively large beam size. Hence, this obscured hot dust model is qualitatively consistent with our ALMA images.

An alternative explanation for an anomalously low $\alpha$ is dust scattering effects. Our source is likely optically thick, and the maximum grain size, $a_{\text{max}}$, appears to be $a_{\text{max}} \lesssim 100\mu$m ($\alpha < 3$; Figure B1). The frequency variation of dust albedo yields a dimmed thermal emission at certain wavelengths under such condition (Liu 2019; Zhu et al. 2019). Note that dust polarization structure has been found to be consistent with dust scattering in the disk of L1527 IRS (Segura-Cox et al. 2015; Harris et al. 2018). The above two possibilities to explain the anomalous $\alpha$ are not mutually exclusive. Both of them can work in our case.

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### Table A2
Summary for JVLA Images

| Label                     | Included Observing Tracks | Briggs Robust Parameter | Synthesized Beam ($\theta_{\text{maj}} \times \theta_{\text{min}}$, P.A.) | Rms Noise Level (mJy beam$^{-1}$) | Recovered Flux (mJy) | Peak Intensity (mJy beam$^{-1}$) |
|---------------------------|---------------------------|-------------------------|------------------------------------------------------------------|-----------------------------------|----------------------|-----------------------------------|
| C band                    | #1-6                      | 0.026 x 0.023; -65°     | 0.027                                                            | 0.65                              | 0.71                 |
| K band                    | #1-6                      | 0.005 x 0.0075; -82°    | 0.066                                                            | 1.1                               | 0.59                 |
| Q band                    | #2-6                      | 0.087 x 0.068; 76°      | 0.11                                                             | 3.7                               | 0.96                 |
| Band 3                    | #7-9                      | 0.155 x 0.068; -2°      | 0.020                                                            | 23                                | 5.4                  |
| Band 4                    | #10-11                    | 0.195 x 0.133; -5°      | 0.15                                                             | 73                                | 1.6                  |
| Band 7                    | #12-13                    | 0.072 x 0.067; -11°     | 0.15                                                             | 370                               | 1.9                  |
| C band A+B config.        | #1-6                      | 0.026 x 0.023; -65°     | 0.027                                                            | 0.65                              | 0.71                 |
| C band A config.          | #1-3                      | 0.026 x 0.023; -65°     | 0.028                                                            | 0.81                              | 0.72                 |
| C band B config.          | #4-6                      | 0.072 x 0.064; 78°      | 0.031                                                            | 0.50                              | 0.51                 |
| K band A+B config.        | #1-6                      | 0.095 x 0.075; -83°     | 0.066                                                            | 1.1                               | 0.59                 |
| K band A config.          | #1-3                      | 0.013 x 0.0099; -66°    | 0.036                                                            | 2.1                               | 0.77                 |
| K band B config.          | #4-6                      | 0.024 x 0.021; 82°      | 0.020                                                            | 1.0                               | 0.81                 |
| Q band A+B config.        | #2-6                      | 0.087 x 0.068; 76°      | 0.11                                                             | 3.7                               | 0.96                 |
| Q band A config.          | #2-3                      | 0.084 x 0.070; -72°     | 0.13                                                             | 3.7                               | 1.4                  |
| Q band B config.          | #4-6                      | 0.13 x 0.011; 86°       | 0.061                                                            | 3.7                               | 1.3                  |
| Q band B1 config.         | #4                        | 0.12 x 0.011; -40°      | 0.10                                                             | 3.6                               | 1.3                  |
| Q band B2 config.         | #5                        | 0.18 x 0.094; 81°       | 0.098                                                            | 3.7                               | 1.1                  |
| Q band B3 config.         | #6                        | 0.14 x 0.012; -71°      | 0.10                                                             | 3.8                               | 1.6                  |
Appendix C
Inspection for Robustness of Detected Substructure

To assess robustness of the detected clumps in the Q-band image, we fit all of the Q-band data with triple 2D-Gaussians. Resulting fitting parameters are summarized in Table C1. Figure C1 compares the resulting fit images with the original images. We have confirmed that all of the data is well fit by triple 2D-Gaussians, and the clumps are detected at consistent positions over multi-epoch independent observations. We have also performed synthetic observations of an infinitesimally thin, smooth disk with the VLA A- and B-configurations. Figure C2 shows an example of our synthetic observations. Flux is sufficiently recovered with the VLA B-configuration, while ~80% of flux is lost with VLA A-configuration. A smooth disk appears not to explain the detected clumps, and thus we conclude the clumps to be physical origin (see the main text for more detailed discussions).
Figure C1. Original $Q$-band image and triple 2D Gaussian fit for each of array configurations. The cyan contours show 1$\sigma$, 2$\sigma$, and 3$\sigma$ levels of the original images and are the same between the right and left panels.

Figure C2. Examples of our synthetic observations. (Left) model emission of a smooth disk with $\Sigma_0 = 10^4$ g cm$^{-2}$ and $i = 10$ deg. The corresponding flux density is $\approx 4.9$ mJy. (middle) observed image with VLA B-configuration and integration time of an hour. Recovered flux density is $\approx 4.3$ mJy (right) observed image with VLA A-configuration and integration time of two hours. Recovered flux density is $\approx 0.84$ mJy.
Table C1
Results of Triple 2D Gaussian Fitting for JVLA Q-band Images. \(D_{NC}\) and \(D_{CS}\) are the Distances between Clump-N and -C, and between Clump-C and -S, Respectively. Computed from the Fitting Results

| Configuration | Clump | \(a\) (K) | \(x\) (au) | \(y\) (au) | \(\sigma_x\) (au) | \(\sigma_y\) (au) | P.A. (rad) |
|---------------|-------|-----------|-----------|-----------|----------------|----------------|-----------|
| ACon | N | 53.2 ± 1.16 | -0.596 ± 0.0892 | 12.1 ± 0.16 | 10.1 ± 0.133 | 2.32 ± 0.039 | 2.09 ± 0.00429 |
| | C | 94.3 ± 0.492 | -2.22 ± 0.0357 | -1.39 ± 0.0749 | 8.54 ± 0.0952 | 4.65 ± 0.0381 | 1.77 ± 0.0108 |
| | S | 69 ± 0.995 | -1.19 ± 0.0528 | -17.3 ± 0.0489 | 4.22 ± 0.0616 | 2.43 ± 0.0382 | 2.45 ± 0.0163 |
| BCon | N | 112 ± 2.95 | -1.5 ± 0.0613 | 5.55 ± 0.196 | 4.04 ± 0.0966 | 5.16 ± 0.0463 | -1.95 ± 0.0356 |
| | C | 120 ± 3.21 | -4.11 ± 0.106 | -2.27 ± 0.137 | 3.88 ± 0.0961 | 5.86 ± 0.0443 | -1.74 ± 0.0208 |
| | S | 102 ± 0.824 | -2.93 ± 0.038 | -15.8 ± 0.0521 | 4.4 ± 0.0519 | 4.65 ± 0.0377 | -1.74 ± 0.112 |

| Configuration | \(D_{NC}\) (au) | \(D_{CS}\) (au) |
|---------------|-----------|-----------|
| ACon | 13.6     | 15.9      |
| ACon | 16.3     | 14.6      |
| B1Con | 15.4 | 18       |
| B3Con | 21      | 18.7      |
| BCon | 14.9     | 16.3      |

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