Local Enhancement of the Surface Density in the Protoplanetary Ring Surrounding HD 142527

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Abstract

We report on ALMA observations of the dust continuum, and $^{13}$CO $J = 3-2$ and C$^{18}$O $J = 3-2$ line emission toward a gapped protoplanetary disk around HD 142527. The outer horseshoe-shaped disk shows a strong azimuthal asymmetry in the dust continuum with a ratio of $\sim$ 30 to 1 at 336 GHz between the northern peak and the south-western minimum. In addition, the maximum brightness temperature of 24 K at its northern area is exceptionally high at 160 au from a star. To evaluate the surface density in this region, the grain temperature needed constraining, and was estimated from the optically thick $^{13}$CO $J = 3-2$ emission. The lower limit of the peak surface density was then calculated to be 28 g cm$^{-2}$ by assuming a canonical gas-to-dust mass ratio of 100. This finding implies that the region is locally too massive to withstand self-gravity, since Toomre’s $Q \lesssim 1-2$, and thus it may collapse into a gaseous protoplanet. Another possibility is that the gas mass is low enough to be gravitationally stable, and only dust grains are accumulated. In this case, a lower gas-to-dust ratio by at least 1 order of magnitude is required, implying the possible formation of a rocky planetary core.

Key words: instabilities — stars: individual (HD 142527) — stars: planetary systems: formation — stars: planetary systems: protoplanetary disk — submillimeter

1. Introduction

In order to find the way planets form, it is critical and most straightforward to observe the actual process of planet building at their birthplaces (Beckwith et al. 1990; Williams & Cieza 2011). The key approach is to determine the detailed structure of a protoplanetary disk, which can provide an indicator of planet-forming activity (Muto et al. 2012). Great attention has therefore been paid to transitional disks with holes or gaps in the materials (Strom et al. 1989; Andrews et al. 2011). Such structures are often interpreted as being a consequence of the occurrence of giant planets that can clear the disk along their orbits. From another perspective, the outer ringlike disk, itself, may serve as a clue to the cause of planet formation (Mathews et al. 2012; Mayama et al. 2012; Pinilla et al. 2012).

HD 142527 is a Herbig Fe star (Waelkens et al. 1996) surrounded by a disk exhibiting a wide gap with a radial width of approximately 100 au (Fukagawa et al. 2006; Fujiwara et al. 2006; Verhoeff et al. 2011, hereafter V11; Rameau et al. 2012; Casassus et al. 2012). The distance is assumed to be 140 pc in this paper, considering its association with Sco OB2. The stellar mass and age are $\sim 2 M_\odot$ and 5 Myr, respectively, estimated by adopting 140–145 pc (Fukagawa et al. 2006; V11). Most recently, faint streamlike features were found in the HCO$^+$ and dust continuum at 345 GHz with ALMA; these were interpreted as being funnel flows into the inner disk through giant planets (Casassus et al. 2013). Here, we revisit the disk structure based on our ALMA data with higher sensitivity and angular resolution. We confirmed the presence of the inner disk, and particularly emphasize the surprisingly high surface density of dust at 160 au from the star in this letter.

2. Observations and Data Reduction

HD 142527 was observed with ALMA in Band 7 by using 20–26 m antennas in the Extended array configuration in...
Cycle 0. The maximum and minimum baselines were 380 m and 20 m, respectively, and the latter corresponded to the largest angular scale of the detectable component of 10". The observations reported in this letter consisted of four scheduling blocks over the period from 2012 June to August. The correlator was configured to store dual polarizations in four separate spectral windows with a bandwidth of 469 MHz and with 3840 channels, providing a channel spacing of 0.122 MHz (0.11 km s\(^{-1}\)). Note that the effective spectral resolution is lower by a factor of ~2 (~0.2 km s\(^{-1}\)) because of Hanning smoothing. The central frequencies for these four windows are 330.588, 329.331, 342.883, and 342.400 GHz, respectively, allowing us to observe molecular lines of \(^{13}\)CO \(J = 3-2\), \(^{18}\)O \(J = 3-2\), and CS \(J = 7-6\). The results of the CS observations will be reported elsewhere. The quasars 3C279 and QSO J1924–2914 were targeted as bandpass calibrators, whereas the amplitude and phase were monitored through observations of the quasar QSO B1424–41. The absolute flux density was determined from observations of Titan and Neptune.

The data were calibrated and analyzed by using the Common Astronomy Software Applications package, version 3.4. After flagging the aberrant data and calibrating the bandpass, gain, and flux scaling, the corrected visibilities were imaged and deconvolved by using the CLEAN algorithm with Briggs weighting with a robust parameter of 0.5. In addition, to improve the sensitivity and image fidelity, the self-calibration was performed for the continuum the distinct structure of which was detected with a very high signal-to-noise ratio (S/N). We started with the CLEAN-ed image as an initial model of the source brightness distribution. The phase alone was first corrected via six iterative model refinements; then, the calibration was obtained for the phase-plus-amplitude without iteration. The solution for the continuum was applied to \(^{13}\)CO and \(^{18}\)O data. The final CLEANing was performed with Uniform weighting for both the continuum and emission lines. The self-calibration reduced the fluctuation in the continuum to a level that 2–3 times the brightness of the theoretical thermal origin can account for, resulting in clear detection of compact emission at the stellar position.

Uncertainty associated with the absolute flux density is 10%.

3. Results

3.1. Continuum at 336 GHz

3.1.1. Outer disk

Figure 1 shows the continuum emission at 336 GHz (890 \(\mu\)m). The outer disk was readily detected, and the total
flux density (> 5σ) was measured as being 2.7 Jy. It significantly departs from a uniform ring, and exhibits a horseshoe-like distribution, as reported on in previous studies (Ohashi 2008; Casassus et al. 2013). The northern region is brighter than the southwestern (SW) area, with an emission peak of 213 mJy beam⁻¹ at a projected distance of 1°0 (140 au) from the star, and at a PA of 30°. When the continuum is probed along the annular emission ridge, both ends of the horseshoe appear to connect at the brightness minimum of 7 mJy beam⁻¹ at 1°3 (180 au) and PA = 220°. The contrast in the flux density thus reaches to the ratio 30:1 between the northern peak and the SW minimum. The peak flux density is expressed by a brightness temperature (T_b) of 24 K without the Rayleigh–Jeans approximation. This T_b is much higher than those beyond 100 au in other disks. Unless the emitting grains are significantly warmer than 24 K, the region should be optically thick to submillimeter radiation due to its high column density.

3.1.2. Inner disk and radial gap

At the position of the star, emission was detected with a significance of 16σ at the peak (figure 1). The χ²-fitting of an elliptic Gaussian function resulted in a FWHM of (0.33 ± 0.02) × (0.29 ± 0.02) with a PA of 99° ± 3° for the major axis. It was thus spatially unresolved, if given the beam size of 0.39 × 0.34. The integrated flux density over the Gaussian was 2.3 ± 0.2 mJy, substantially higher than the photospheric level of 0.02 mJy. This suggests that the emission comes from the inner disk, whose presence has been predicted from the near-infrared excess, and the mid-infrared imaging (V11; Fujiwara et al. 2006) where the inner disk was marginally resolved with an inferred size of 30–50 au in radius. The gaseous emission from the inner disk was also imaged and kinematically resolved (Casassus et al. 2013; Öberg et al. 2011; Pontoppidan et al. 2011). The mass of the inner disk (M_in) can be crudely estimated, assuming that the majority of the mass resides in the outer, optically thin part, by using the equation M_in = F_v d²/[κ_v B (T)], where F_v is the observed flux density, d the distance to the star, κ_v the opacity, and T the characteristic temperature of the disk. We adopted T = 50 K (Chiang & Goldreich 1997) and κ_336 of 0.034 cm²g⁻¹, assuming a gas-to-dust mass ratio (hereafter, referred to as “g/d”) of 100, on the basis of the conventional relation κ_v = 0.1(/10¹² Hz)^[β] cm²g⁻¹ with β = 1.0 (Beckwith et al. 1990; V11); then, we calculated that the total (gas and dust) disk mass is (4.3 ± 0.4) × 10⁻² M_O. Note that a considerable uncertainty exists in the assumption of optical thickness, and the mass derived here can give a lower limit. In the previous modeling of the spectral energy distribution, the dust (not including gas) mass of the inner disk was estimated to be 2.5 × 10⁻⁹ M_O, but the model was constrained primarily based on the near- and mid-infrared excess and the assumption of grains of size ~ 1 micron (V11). The flux density at 890 μm obtained with ALMA seems to be by about one order of magnitude higher than that expected in their modeling. The detection of the submillimeter continuum in our imaging suggests that the bulk of the mass resides in grains of larger size.

In the radial gap, the surface brightness decreases to the background level. Dust streamers from the outer disk reported on in a previous study (Casassus et al. 2013) were not confirmed.

3.2. 13CO J = 3–2 and C¹⁸O J = 3–2

3.2.1. Integrated intensity and gas kinematics

The left panels of figure 2 present integrated intensity (0th-moment) maps of the 13CO J = 3–2 and C¹⁸O J = 3–2 line emission. The brightness distributions do not show such a strong azimuthal asymmetry as that observed in the dust continuum, and fluctuate by a factor of less than 2. In the radial direction, the integrated intensity has peaks at a range of r = 0°7–1°1, depending on the position angle in 13CO, and at r = 0°8–1°2 in C¹⁸O. No emission was detected above 3σ around the stellar position in both lines (1σ = 18.9 and 19.6 mJy beam⁻¹ km s⁻¹ for 13CO and C¹⁸O, respectively).

The right panels of figure 2 show 1st-moment maps in 13CO and C¹⁸O. Despite the highly structured continuum, the velocity fields are consistent with a simple, circular Keplerian motion within a resolution of 0.2 km s⁻¹, which was confirmed as follows. The position–velocity relation was extracted along the major axis (PA = −19° ± 2°), and the peak velocity was estimated by Gaussian fitting at each radius at the interval of 0°3. Then, an S/N-weighted least-squares fitting of an analytic Kepler equation was performed to the measured peak velocity as a function of the radius. In the fitting, the systemic velocity, position of the center of mass (the star), and inclination relative to the observer were a set of free parameters, whereas the stellar mass was fixed at the range of 2.2 ± 0.3 M_O (V11). By using the 13CO data with a higher S/N, the inclination was estimated to be i = 26°9±7°1, where the uncertainty is dominated by the error in the adopted stellar mass. Note that i is not large enough to yield reasonable (|ΔΔV| < 10°, |ΔM_☉| < 50%) constraints on both the inclination and the stellar mass (Simon et al. 2000). We determined that the systemic velocity is 3.70 ± 0.02 km s⁻¹. The location of the velocity centroid matches with the compact component of the continuum emission within a range of 0.04.

3.2.2. Temperature estimate

The line results mentioned above were obtained after subtracting the underlying continuum, by the same method that was adopted in earlier studies. However, the continuum from the outer disk of HD 142527 shows strong azimuthal asymmetry of T_b (sub-subsection 3.1.1). In fact, the peak-intensity maps of 13CO and C¹⁸O most evidently show a flux deficit in the north. When the T_b map of the continuum is added to that of the line peak intensity, after matching the beam size to each of the line data, the resultant distribution of T_b(13CO) is ring-like and azimuthally uniform (figure 3). In the radial direction, the maximum T_b(13CO) is 41 K at 40 au inside the peak of the continuum, when measured in the deprojected (i = 27°) profile averaged in a position angle range of from −49° to 51° for the bright continuum. The T_b(13CO) at the location of the continuum peak is 36 K, and it happens to coincide with the highest T_b(C¹⁸O) inwardly located 28 au apart from the continuum peak.

The optical depth of 13CO is greater than unity over the entire disk detected above 5σ in C¹⁸O, judging from the continuum-subtracted ratio between the C¹⁸O peak intensity and the 13CO intensity at the same velocity as C¹⁸O. Here, we assume the same excitation temperature (T_k) for both lines and an abundance ratio of X(C¹³O)/X(C¹⁸O) ~ 7 (Qi
et al. 2011). In addition, except for the SW region, \( T_b(\text{C}^{18}\text{O}) \) is systematically lower by \( \sim 5 \text{ K} \) than \( T_b(\text{C}^{13}\text{O}) \) in the outer region beyond the radial \( T_b \) peak; this relation can be naturally understood to mean that the line emission comes from optically thick surfaces in the upper layer for \( \text{C}^{13}\text{O} \) and in the lower for \( \text{C}^{18}\text{O} \). Moreover, the radial shifts of the highest \( T_b \) for the lines from that for the continuum can be attributed to the inner, warmer emitting surfaces for the gaseous component exposed to the central star. Therefore, the line intensity, at least for \( \text{C}^{13}\text{O} \), reflects the physical (kinetic) temperature and not the column density under local thermodynamic equilibrium (LTE). The emission can be approximated by the LTE conditions because the density that will be discussed below (see sub-subsection 4.1) is well above the critical densities for \( \text{C}^{13}\text{O} \) and \( \text{C}^{18}\text{O} \) at 3–2 (Pavlyuchenkov et al. 2007). In order to estimate the temperature of the optically thick surface, the continuum needs adding, since it is non-negligible for this object.

4. Discussion

4.1. Constraint on the Surface Density

The bulk of grains is expected to be closer to the disk mid-plane, and it is unlikely that it is warmer than the emitting surfaces in \( \text{C}^{13}\text{O} \) and \( \text{C}^{18}\text{O} \) in the outer region beyond the radial \( T_b \) peak; this relation can be naturally understood to mean that the line emission comes from optically thick surfaces in the upper layer for \( \text{C}^{13}\text{O} \) and in the lower for \( \text{C}^{18}\text{O} \). Moreover, the radial shifts of the highest \( T_b \) for the lines from that for the continuum can be attributed to the inner, warmer emitting surfaces for the gaseous component exposed to the central star. Therefore, the line intensity, at least for \( \text{C}^{13}\text{O} \), reflects the physical (kinetic) temperature and not the column density under local thermodynamic equilibrium (LTE). The emission can be approximated by the LTE conditions because the density that will be discussed below (see sub-subsection 4.1) is well above the critical densities for \( \text{C}^{13}\text{O} \) and \( \text{C}^{18}\text{O} \) at 3–2 (Pavlyuchenkov et al. 2007). In order to estimate the temperature of the optically thick surface, the continuum needs adding, since it is non-negligible for this object.

4.2. Spatial Structure

The radial profile for the continuum emission is well described by a Gaussian function, rather than a power law, at all position angles. A Gaussian fitting to the deprojected, azimuthally averaged profile gave \( I_{\text{average}} \) (Jy beam\(^{-1}\)) = \( 9.95 \times 10^{-2} \exp\left[-\left((R - 161.1)/(48.2)\right)^2\right] \), where \( R \) is the distance from the star in au. Assuming a g/d of 100 and a temperature of 36 K, the Gaussian fitted to the azimuthally averaged profile has a peak surface density, \( \Sigma_{\text{average}} \), of 11.3 g cm\(^{-2}\) at \( R = 161 \) au. The Gaussian fitting to the radial profile in each \( PA \) yielded one clear feature, which is anticorrelation between the peak intensity of the Gaussian and its deprojected distance from the star (figure 4). This anticorrelation excludes the possible explanation that the azimuthal asymmetry is due to eccentric orbits of the dust particles. If the orbits are eccentric, they concentrate near the apastron.

If the density profile is confirmed to be Gaussian after incorporating a realistic temperature gradient, it is natural to understand the disk as being a ring or torus. In a primordial disk, the radial distribution of the surface density can be expressed as a power law accompanied by an outer, exponential tapered edge (Hughes et al. 2008). An inner gap or hole can then be created by being carved by a planet(s), for instance, but the outer boundary should remain unaffected unless the gap stretches to nearly the outer edge of the disk or the source experiences stellar encounters. It would be worth noting that the formation of a ring can be explained by different mechanisms without the aid of planets, such as a secular process through viscous overstability (S. Z. Takahashi & S. Inutsuka in preparation; Schmit & Tscharnuter 1995).

On the other hand, the \( \text{C}^{13}\text{O} \) emission was detected so far as \( r \sim 350 \) au on average at all position angles (5\( \sigma \), figure 3), which is not reconciled with the Gaussian profile for the continuum. The \( \text{C}^{13}\text{O} \) intensity at 350 au is by several orders of magnitude higher than that predicted by an extrapolation from the Gaussian for any excitation temperature, assuming LTE and a g/d of 100. This suggests an additional floor spreading outward. The nondetection of the dust continuum for this floor is not inconsistent with the assumption of a g/d of 100, considering the detection limit in our observations.
4.3. Stability against Self-Gravity

What can be expected from the local density enhancement in a Keplerian disk? To evaluate the gravitational stability, Toomre’s $Q$ parameter (Toomre 1964) was computed under the assumption of a $g/d$ of 100. It was first estimated toward the averaged surface density to examine the global stability, resulting in $Q(R = 161 \text{ au}) = 2.2$ using $\Sigma_{\text{average}} = 11 \text{ g cm}^{-2}$, the isothermal sound speed for $36 \text{ K}$, and a stellar mass of $2.2 M_\odot$. Locally estimated at the horseshoe peak at $R = 156 \text{ au}$, $Q$ was found to be $0.9$ for $\Sigma_{\text{peak}} = 28 \text{ g cm}^{-2}$. Note that $\Sigma$ is at its lower limit, whereas the temperature (sound speed) is the upper limit; therefore, the obtained $Q$ is considered to provide the upper limit. $Q \lesssim 1$ indicates that the disk is vulnerable to gravitational instability if $g/d$ is $\sim 100$. Crudely assuming that a resultant fragment acquires the mass within a local volume of the size of the disk scale height ($16 \text{ au at } 36 \text{ K}$), it gains $\sim 3$ Jupiter-masses. The dynamical clumping of the ring structure can provide a fresh insight into the origin of wide-orbit planetary bodies (Marois et al. 2008; Ireland et al. 2011).

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