A Cavity of Large Grains in the Disk around the Group II Herbig Ae/Be Star HD 142666

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Abstract

Herbig Ae/Be (HAeBe) stars have been classified into Group I or Group II, and were initially thought to be flared and flat disks, respectively. Several Group I sources have been shown to have large gaps, suggesting ongoing planet formation, while no large gaps have been found in the disks of Group II sources. We analyzed the disk around the Group II source, HD 142666, using irradiated accretion disk modeling of the broadband spectral energy distribution along with the 1.3 mm spatial brightness distribution traced by Atacama Large Millimeter and Submillimeter Array (ALMA) observations. Our model reproduces the available data, predicting a high degree of dust settling in the disk, which is consistent with the Group II classification of HD 142666. In addition, the observed visibilities and synthesized image could only be reproduced when including a depletion of large grains out to ∼ 16 au in our disk model, although the ALMA observations did not have enough angular resolution to fully resolve the inner parts of the disk. These results may suggest that some disks around Group II HAeBe stars have cavities of large grains as well. Further ALMA observations of Group II sources are needed to discern how commonly cavities occur in this class of objects, as well as to reveal their possible origins.

Key words: accretion, accretion disks – planets and satellites: formation – protoplanetary disks – stars: individual (HD 142666) – stars: pre-main sequence

1. Introduction

Protoplanetary disks have long been thought to be the birthplaces of planetary systems. Early models of dust evolution predicted that the dust inherited from the ISM grew by colliding, sticking together, and settling toward the disk midplane, where further interactions made them grow toward planetesimals and planets (Weidenschilling 1997). Observations have supported and expanded this view; in particular, they have revealed disk structures that have been attributed to interactions between the disk and forming planets (cf. Espaillat et al. 2014).

Before the advent of high-spatial resolution instruments, disk properties were often inferred from studies of the spectral energy distributions (SEDs) of young objects. In particular, such studies have focused on young, intermediate-mass stars, known as Herbig Ae/Be stars (HAeBe) (Waters & Waelkens 1998), which have been separated into two groups, Group I and Group II. This classification came from fitting the mid-IR (15–45 μm) portion of HAeBe stars’ SEDs. The SEDs of Group I stars required both a blackbody and power law to fit, while those of Group II stars could be fit with only a power law (Meeus et al. 2001). On average, it was noted that Group I stars have larger IR excesses when compared with Group II stars (Dominik et al. 2003), which has been quantified using IRAS (van Boekel et al. 2003) and Herschel data (Pascual et al. 2016). Specifically, the latter study found that Group II sources have a lower ratio of far-IR (20–200 μm) to near-IR (2–5 μm) flux than do Group I sources. In turn, these differences have been interpreted as Group I objects having “flared” disks and Group II objects having “flat” disks. Flared disks are defined such that the height of the disk increases rapidly with radius, capturing more stellar light, and therefore being hotter (Kenyon & Hartmann 1987) than flat disks. In fact, flared, Group I sources were thought to evolve into flatter, Group II sources due to dust growth and settling (Dullemond & Dominik 2004).

However, further differences were found that brought into question the evolutionary relationship between the groups. SED modeling (~0.1–1000 μm), together with N-band, Q-band, and 25 μm imaging, revealed that many Group I sources have large, >20 au, inner gaps or cavities (e.g., Maaskant et al. 2013; Honda et al. 2015). In contrast, based on N-band interferometry, Group II sources have only showed evidence of smaller, <1 au gaps close to the dust sublimation radius (e.g., HD 142666, HD 144432; Menu et al. 2015).

The Atacama Large Millimeter and Submillimeter Array (ALMA) has provided images of protoplanetary disks with extreme detail, revealing substructures, such as narrow gaps and rings, that could not previously be studied (ALMA Partnership et al. 2015; Andrews et al. 2016). For Group II sources, prior ALMA observations have often focused on the disk’s chemical content, gas dynamics, or disk asymmetries instead of substructures like gaps or cavities (Czekala et al. 2015; Guzmán et al. 2015; Kataoka et al. 2016; White et al. 2018). Recently, though, ALMA observations revealed shallow, >20 au gaps around the Group II source HD 163296 (Isella et al. 2016; Zhang et al. 2016; MuroArena et al. 2018), suggesting the possible presence of gaps or cavities in other Group II sources.

Here, we study the Group II HAe star HD 142666 (V1026 Sco, Mees et al. 2001), located in the Upper Sco OB-2 association (Sandell et al. 2011; d = 150.1 pc; Gaia Collaboration et al. 2016a). HD 142666 has been observed from near-IR wavelengths, detecting the scattered light from the disk (Garufi et al. 2017), to submillimeter wavelengths, detecting the unresolved emission from the 12CO J = 2–1 (Panić & Hogerheijde 2009) and 12CO J = 3–2 (Dent et al. 2005) rotational lines.

Some structure has also been found in the disk of HD 142666. From SED modeling and interferometric observations
in the 1.6–2.5 μm and 8–13 μm wavelength ranges, Schegerer et al. (2013) inferred the existence of a hole in the disk inside 0.3 au and a dust-free gap between 0.35 and 0.8 au. On the other hand, Banzatti et al. (2018) found evidence for no or a very small cavity for this disk in their study combining near-IR (1.2–4.5 μm) and CO rovibrational emission. So far, no evidence has suggested the presence of a large gap or cavity around HD 142666, comparable to those found in Group I sources.

In this paper, we present a physically self-consistent model of the SED and ALMA observations for the disk around HD 142666. In Section 2.1, we describe the archival photometry and spectra used for the SED modeling. In Section 2.2, we present archival 1.3 mm (Band 6) ALMA observations, and we show the results of an initial analytical fit to the observations. In Section 3.1, we describe the model and physical parameters used to reproduce the observations. In Section 3.2, we summarize the results, including a cavity extending radially out to ∼16 au in the disk’s large dust grain distribution. Finally, in Section 4, we put this large cavity in context with relevant results involving cavities and gaps in HAeBe disks.

2. Observations and Results

2.1. Stellar Properties and the SED

To construct the SED of HD 142666 and its disk (Figure 1), we gathered the IRS spectrum (Keller et al. 2008) and visible to mm photometry from 2MASS, AKARI, IRAS, Tycho-2, WISE, and van der Veen et al. (1994), Sylvester et al. (1996), Malfait et al. (1998), Natta et al. (2004), Meeus et al. (2012), Mendigutía et al. (2012), and Pascual et al. (2016). We note that we did not include photometry that overlapped with the IRS wavelengths (e.g., From AKARI or WISE) in order to avoid the wide bandpasses of these filters.

The data were reddenning using the Mathis (1990) reddening law by first finding the extinction $E(B - V)$ from the observed $B - V$ color and the intrinsic $(B - V)_{0}$ color from Kenyon & Hartmann (1995). Assuming $RV = 3.1$, we obtained $A_V = 0.992$. The stellar luminosity was then derived using the reddened V-band magnitude. This luminosity, together with the effective temperature, was compared with evolutionary tracks (Siess et al. 2000) to obtain a stellar mass. These stellar properties are shown in Table 1.

Although the mass accretion rate ($\dot{M}$) for HD 142666 has been measured to be between $1 \times 10^{-8}$ and $2 \times 10^{-7} \text{M}_\odot \text{yr}^{-1}$ (Garcia Lopez et al. 2006; Donehew & Brittain 2011; Mendigutía et al. 2011; Salyk et al. 2013). Even though the range in these measurements could be due to intrinsic variability, these papers used different methods, making comparison difficult.

2.2. ALMA Observations

We used Cycle 2 ALMA archival observations (PI: L. Pérez) of the protoplanetary disk of HD 142666. The data were calibrated using the reduction package Common Astronomy Software Applications (CASA: McMullin et al. 2007). HD 142666 was observed on 2015 July 21 at Band 6 using an array of 44 antennas. The observations were flux-calibrated with the QSOs J1517-2422 and J1627-2426 and bandpass-calibrated with Titan. The total on-source time was 59.04 minutes. Two spectral windows (SPW) centered at 216.974 and 232.349 GHz were used to detect the continuum, each with a bandwidth of 1.875 GHz.

We used the CLEAN task in CASA interactively to obtain deconvolved images from the observed visibilities. We chose a uniform weighting, resulting in a synthesized beam of 0″200 × 0″165 and an rms sensitivity of 0.22 mJy beam$^{-1}$. The lower left panel of Figure 2 shows the resulting 1.38 mm continuum image. The continuum emission shows a resolved, compact disk without apparent evidence of non-axisymmetry or a gap.

Enclosing the source inside a 1″ × 1″ box, we estimated a flux density of 113 ± 6 mJy, consistent with the results of a Gaussian fit to the image. The Gaussian fit was also used to estimate the central coordinates, position angle (PA; 161°), FWHM (30 au), and inclination (∼60°) of the disk.

Finally, we changed the phase center and deprojected the visibilities using small shifts in position, as well as different values of inclination and PA. The values that resulted in the minimum scatter in the real and imaginary parts of the visibilities were consistent with the results found by the Gaussian fit. The measured inclination agrees with previous studies based on $H$-band interferometric observations (Lazareff et al. 2017) and modeling of mid-IR interferometry (Vural et al. 2014).

In Figure 3, we show the deprojected, real part of the visibilities. We note that the ALMA continuum observations are split into two SPWs that are separated by ∼15 GHz but have a high SNR individually. Thus, we have analyzed both SPWs separately and only show the results for the SPW centered at 216.974 GHz (1.38 mm). The visibilities show a very steep decrease followed by a null at ∼500 kλ, suggesting the presence of a cavity in the disk (Hughes et al. 2007). To characterize the disk’s intensity profile, we fit the visibilities...
using a parametric model of the surface brightness profile of the disk as in Zhang et al. (2016). The top panels of Figure 3 show the results of this modeling. The resulting intensity profile shows a drop in intensity at \( R < 9.5 \) au. We used this intensity profile as a first estimate for the following physical disk modeling.

3. Modeling

3.1. Modeling Procedure

We modeled the SED and ALMA continuum observations of HD 142666 using the physically self-consistent disk model by D’Alessio et al. (2006). The model computes the radial and vertical structure of an irradiated accretion disk while also enforcing hydrostatic equilibrium. It includes a wall at the inner edge of the disk that is directly irradiated by the star. In addition, we added a tapered edge to the disk’s surface density profile following \( e^{-R/R_d} \), where \( R_d \) is the outer disk radius at which the tapering begins, and \( \gamma \) determines its steepness. The viscosity is described by the parameter \( \alpha \) following Shakura & Sunyaev (1973). We left it fixed because of its degeneracy with \( M \) (D’Alessio et al. 2006). The dust in the disk was described by two populations of grains with size distributions \( n(a) \propto a^{-3.5} \) between a minimum size, \( a_{\text{min}} = 0.005 \) \( \mu \text{m} \), and maximum size, \( a_{\text{max}} \), which was kept as a free parameter. The large grains \( (a_{\text{mid}}) \) were concentrated at the midplane of the disk, while the small grains \( (a_{\text{max}}) \) were located mostly in the upper layers (D’Alessio et al. 2006). To include dust settling, the population of small grains in the disk atmosphere was depleted by a factor \( \epsilon \), which is the ratio of the dust-to-gas mass ratio of small grains to the standard dust-to-gas mass ratio. The dust-to-gas mass ratio of the large grains in the midplane was increased to conserve the standard mass ratio at each radius (D’Alessio et al. 2006). The wall emission was calculated following D’Alessio et al. (2005). The maximum grain size in the wall at the dust destruction radius, as well as the dust sublimation temperature, \( T_{\text{wall}} \), and the height of the wall, \( z_{\text{wall}} \), were kept as free parameters.

Following the results of the parametric model of the surface brightness profile (Section 2.2), we also included a cavity in the distribution of large dust grains in some models. Here, we define “cavity” as a region of the disk in which dust is significantly depleted. We note that the near-IR and mid-IR parts of the SED, which traced the small dust grains located close to the star, did not show significant depletion. Therefore, we included an inner cavity in our model by decreasing the abundance of only the large grains out to \( R_{\text{cav}} \) by a factor \( \delta_{\text{cav}} \).

We considered combinations of parameters using a grid of disk models. The range of values explored is shown in Table 2. The inclination, \( i \), and \( R_{\text{cav}} \) of the disk were initially constrained using the ALMA observations (Section 2.2). From the grid of parameters tested, the models that best fit the SED were obtained by minimizing the \( \chi^2 \). A synthetic image of each model was computed. The images were then Fourier-transformed and sampled with the UV coverage of the ALMA observations, obtaining the simulated visibilities of the model. From these visibilities, an image was obtained using the
CLEAN task in CASA. The simulated visibilities and images were compared with the observed visibilities and the averaged radial profile of the disk, respectively.

3.2. Disk Properties

Figure 1 shows the final fit to the SED, and Figure 2 shows the model (middle) and residual (right) images. The fits to the real part of the visibilities and to the radial profiles are shown in the lower panels of Figure 3. The parameters that best fit the SED and ALMA observations are shown in Table 2.

Full disk models always failed to reproduce the visibilities and the inner parts of the radial profile (Figures 2 and 3). We found our best fit to the ALMA observations when including a cavity in the large dust grains out to 15.6 au. Nevertheless, the near-IR and mid-IR range of the SED fit well with a continuous abundance of small grains, suggesting that small dust grains are filling the cavity.

Our best fit also corresponded to an inner edge of the disk (\(R_{\text{wall}}\)) of 1.3 au (Table 2). In comparison, Schegerer et al. (2013) and Vural et al. (2014) obtained inner disk radii of 1.35 au and 0.8 au, respectively. These studies found additional structure inside these radii using near-IR and mid-IR visibilities. We do not attempt to include these constraints in this paper. However, since near-IR emission arises in small dust in the atmospheric layers of the inner disk (D’Alessio et al. 2006), the Schegerer et al. (2013) and Vural et al. (2014) results are consistent with having small dust down to scales \(\sim 1\) au, in agreement with our results.

To find the dust mass of the disk, we integrated the surface density distribution of our best-fit disk model and found a mass of \(5.3 \times 10^{-4} \, M_\odot\). Assuming a dust-to-gas mass ratio of 0.01,
we then found a total disk mass of 0.0533 $M_\odot$, and a mass of $1.55 \times 10^{-7} M_\odot$, for small grains in the disk’s cavity. We also found a high degree of settling in the disk ($\epsilon = 0.001$), which was consistent with the classification of HD 142666 as a Group II source. As indicated by the ALMA observations, the disk of HD 142666 is also fairly compact, with an $R_d$ of 65 au and a relatively sharp edge.

4. Discussion

From the results of our physical irradiated accretion disk model, we have inferred the presence of a cavity in large dust grains out to 15.6 au in the disk of HD 142666. These results are supported by the parametric model, based on the surface brightness profile, that fits the deprojected visibilities and indicates a significant decrease of mm emission at $R < 9.5$ au. Our results are the first evidence of the presence of a wider cavity of large grains in the disk, which may have been elusive in the past because it is present only in the large dust grain distribution traced by the ALMA observations. Group II sources have been proposed to have their outer disks self-shadowed by the inner regions of the disk, which could result in a colder, ring-like region of the disk. Nevertheless, this cannot explain the cavity revealed by the ALMA observations since the radio emission probes dust in the midplane, where a shadow would have a very small effect.

Several mechanisms have been proposed to explain the presence of cavities in protoplanetary disks (Espaillat et al. 2014). One mechanism involves dynamical interactions due to planets in the disk, which have been shown to open cavities and gaps in the dust distribution. Additionally, the edges of these cavities represent local pressure maxima, which can trap large dust grains, while allowing small dust grains to move toward the star and fill the cavity (Zhu & Waelkens 2014). Thus, since the cavity in HD 142666’s disk is present mainly in the large dust grain distribution, this cavity aligns with a planetary origin.

We compare the dust distribution of HD 142666 with that of the Group I object HD 100546. ALMA observations reveal $\sim 10$ au cavities in the large grains in both objects (this work; HD 100546, Pineda et al. 2014). The largest difference is in the distribution of small grains. In HD 100546, small grains populate the disk at radii < 1 au, producing near-IR excess. Small grains also coexist with large grains in the outer disk. But a large region, between $\sim 1$ au and $\sim 10$ au, is essentially depopulated of small grains (based on AMBER/MIDI; Benisty et al. 2010). In contrast, there is no such large gap in the small grains in the disk of HD 142666; they are present in the disk down to $\sim 1$ au (based on AMBER/MIDI; Schegerer et al. 2013; Vural et al. 2014).

More generally, prior studies in the near-IR to mid-IR showed that most Group I sources have large, $>20$ au, inner clearings of dust (Maaskant et al. 2013; Honda et al. 2015), while cavities found in Group II sources have been small, $<1$ au, and detected only close to the sublimation radius (Menu et al. 2015). Together with the proposed structural differences between the disks of Group I and Group II sources as indicated by their SEDs, these different cavities and structures have been explained with two scenarios: different evolutionary stages (a common ancestry) or separate evolutionary paths (Maaskant et al. 2013; Menu et al. 2015; Garufi et al. 2017). Garufi et al. (2017) postulated that as gaps are only present in the disks of Group I sources, the groups were more likely to evolve along separate paths.

Our results have shown that HD 142666 has an inner cavity extending out to $\sim 15.6$ au. In addition, the Group II source HD 163296 was recently shown to have multiple gaps, as well as a possible shallow, inner gap with a width of $\sim 20$ au (Isella et al. 2016; Zhang et al. 2016; Muro-Arena et al. 2018). Although the classification of HD 163296 as Group II has been disputed by Muro-Arena et al. (2018), our results indicate that the characterization of Group I and Group II sources as gapped and continuous disks may not always apply.

The inner cavities and gaps in the disks of Group II sources, like those of HD 142666 and HD 163296, may be smaller and/or shallower than those in the disks of Group I sources, which may also explain why inner cavities and gaps of disks around Group II sources are not evident in SEDs. In fact, the SEDs of other Group II sources set constraints on the size of inner cavities, if present. Thus, even though cavities and gaps can be present in the disks of both Group I and Group II sources, there seems to be differences in the size of cavities and gaps between the the two groups. These differences cannot be explained by a scenario where Group I sources evolve into Group II sources, since inner gaps or cavities are not expected to decrease in size or to be refilled with dust during their evolution. An inverse process could be postulated where the gaps of Group II sources get larger with time so that Group II evolves into Group I (e.g., Menu et al. 2015). However, as pointed out by Garufi et al. (2017), the fact that disks around Group II sources have lower millimeter fluxes and smaller disk sizes than those of Group I sources does not favor this possibility.

Therefore, despite having shown that gaps can be present in disks around both Group I and Group II sources, different evolutionary tracks still seem to be the most likely scenario to explain both groups. The different gap sizes between Group I and Group II could in fact be a direct consequence of these
different evolutionary tracks. If Group I includes denser and more massive disks, then they could be more likely to form giant planets. If so, such planets would open wider and deeper cavities than those around Group II sources, which, if present, would be formed by less massive planets.

In conclusion, our results, together with previous observations of HD 163296, show that the disks of Group II sources can contain cavities or gaps of large grains, despite prior claims. These inner gaps or cavities of large grains may be, however, smaller than those seen around Group I sources. Our detailed modeling of HD 163266 also indicates that no corresponding cavities exist in the small grains. Higher angular resolution observations with ALMA will be necessary to confirm whether cavities are present in the disks of other Group II sources. Such studies will inform how disk structure relates to planet formation.

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