Transition disks: 4 candidates for ongoing giant planet formation in Ophiuchus
(Research Note)

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ABSTRACT

A large set of Spitzer-selected transitional disks in the Ophiuchus molecular cloud was recently examined by Cieza et al (2010), and 4 of the targets were identified as (giant) planet-forming candidates based on the morphology of their Spectral Energy Distributions (SEDs), the apparent lack of stellar companions, and evidence for accretion. Here we characterize the structures of these disks modeling their optical, infrared and (sub)millimeter SEDs. We use the Monte Carlo radiative transfer package RADMC to construct a parametric model of the dust distribution in a flared disk with an inner cavity and calculate the temperature structure consistent with the density profile, in thermal equilibrium with the irradiating star. For each object, we conducted a Bayesian exploration of the parameter space generating Monte Carlo Markov Chains (MCMC) that allow the identification of the best fit parameters and to constrain their range of statistical confidence. Our calculations point to the presence of evacuated cavities with radii $\sim 2 - 8$ AU, consistent with having been carved by embedded giant planets. We found parameter values consistent with those previously given in the literature, indicating a mild degree of grain growth and dust settling, which deserves to be investigated with further modeling and follow up observations. Resolved images with (sub)millimeter interferometers are required to break some of the degeneracies of the models and better constrain the physical properties of these fascinating disks.

Key words. circumstellar matter — planetary systems: protoplanetary disks — stars: pre-main sequence

1. Introduction

The infrared spectral energy distributions (SEDs) of circumstellar transitional disks reveal the presence of an optically thin inner region and an optically thick outer disk. Several mechanisms relevant to the overall evolution of circumstellar disks, and in particular to the short-lived phase when they dissipate, have been proposed to explain the so-called opacity holes of transition disks: giant planet formation, grain growth, photoevaporation, and tidal truncation in close binaries. See Williams & Cieza, 2011 for a recent review. The processes responsible for the inner holes of transition disks can tentatively be distinguished when disk masses, accretion rates, and multiplicity information are available (Najita et al. 2007; Cieza 2008). Following this approach, Cieza et al. (2010, hereafter Paper I) presented the initial results of an ongoing project to characterize a large set of transition disk candidates in nearby star-forming regions.

Probing the structure of disks that are suspected to be forming planets is the most promising approach to understand the conditions in which planets are formed. The best indication for ongoing planet formation in disks is the detection of tidal gaps (e.g. Piétu et al. 2006) corresponding to a ring with significant decrease in the surface density (or the whole inner disk if it was depleted by accretion, e.g. Varneire et al 2006). A spectacular confirmation has arrived with the recent detection of the first potential substellar object within the gap of the transitional disk T Chamaleontis (Huelamo et al. 2011). Inner holes and gaps have already been observed at (sub)millimeter wavelengths in a handful of objects bright enough for resolving disk structure (Piétu et al. 2006; Hughes et al. 2007, 2009; Brown et al. 2008, 2009; Andrews et al. 2009, 2010a, 2011, Isella et al 2010a, 2010b).

Comprehensive studies of similar transition disks are necessary to increase the empirical constraints on their structures and investigate their diversity. This is the primary motivation of this work, where we apply a parametric description to the 4 planet-forming disks candidates in
We consider a surface density profile characterized by a power-law, \( \Sigma \propto R^{-\gamma} \), with an exponential taper at larger radii (\( \Sigma \propto e^{-(R/R_c)^2} \)), where \( R_c \) is the characteristic radius. This is physically motivated by the success of similarity solutions of viscous disks to reproduce the observed gradual density decay at large radii (Hughes et al. 2008). \( \Sigma \) is normalized to obtain the total mass of the disk, \( M_d \), when integrated. The radial index was fixed to be \( \gamma = 1 \) which is a typical value within the range \( 0.4 \sim 1.1 \) established by Andrews et al. (2010a). Our option could be questioned in the light of results by Isella et al. (2009) who have independently inferred slopes from steep to quite shallow in their sample of spatially resolved disks.

Resolved images are therefore mandatory to obtain more accurate estimates of \( \gamma \) for our particular targets. We set the characteristic radius \( R_c = 100 \) AU. However, there is no spatially resolved information in the SEDs alone, and the data can be reproduced equally well with a wide range of outer disk values (Andrews et al. 2010b). The value we choose is representative of the disks with resolved interferometric visibilities, that are \( R_c = 14 \sim 198 \) AU (Andrews et al. 2009, 2010b) in Ophiuchus, and \( R_c \sim 30 \sim 230 \) AU for Taurus-Auriga (Isella, Carpenter & Sargent, 2009). Note that larger outer radii (100 - 1100 AU) have been obtained with different fitting techniques (sharply truncated power law fits to CO observations) and are not directly comparable with the \( R_c \) values (see Williams & Cieza 2011). Aside from the extreme case of a nearly edge-on viewing angle, the disk inclination cannot be determined from unresolved observations. Scattered light images have proven useful in this sense (Pinte et al. 2007). We have set an intermediate representative inclination \( i = 30^\circ \) in our modeling.

3. Radiation transfer models

The modeling that we have applied is similar to those performed by Andrews et al. (2009, 2010a) and Brown et al. (2009), who have confirmed their physical parameters from SED modeling through direct imaging. A 2-D structure model for flared disks is combined with the Monte Carlo continuum radiative transfer package RADMC v3.1 (Dullemond & Dominik, 2004), modified to include a density reduction as an inner cavity. The code computes a temperature structure consistent with the given density profile, and in equilibrium with the irradiation by the central star. The disk is presumed to be passive, an assumption that is supported by the low disk to stellar luminosity ratios of our sample, \( \lesssim 0.005 \) according to estimates in Paper I.

We consider a surface density profile characterized by a

\[
\delta_{\text{cav}} = \frac{\delta_{\text{cav}}}{a} \left( \frac{a}{\lambda_{\text{turn-off}}} \right)^{\gamma - 1} \left( \frac{a}{a_{\text{min}}} \right)^{-1}, \quad a_{\text{min}} = 0.005 \mu \text{m up to } a_{\text{max}} = 1 \text{ mm, and}
\]

\[
\frac{\delta_{\text{cav}}}{a_{\text{min}}} \propto a^{-3.5}, \quad \text{extends in diameters from } a_{\text{min}} = 0.005 \mu \text{m up to } a_{\text{max}} = 1 \text{ mm, and}
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\]
the opacities were calculated with a simple code for Mie scattering.

The stellar properties given in Table 1 are in each case fixed inputs for the models, and Kurucz spectra are used as models of the central stars. As the disk SED is not influenced by the $\lambda \lesssim 3 \mu$m fluxes, they were not included in the final fit, avoiding a systematic error term (shift in the $\chi^2$). For each disk, we have explored the parameter space, $\{M_{\text{disk}}, H_{100}, R_{\text{cav}}, \log \delta_{\text{cav}}\}$, by generation of Monte Carlo Markov Chains, which is a parameter space exploration technique designed to provide the best fitting values and their uncertainties. This technique attains a better performance than classical data fitting methods (e.g., Press et al. 2007). A cavity is also inferred in all 4 cases, with the smallest cavity and is bright enough to be detected by SMA when possible (or using the larger side if not) was used to define the error estimates within a conservative approach.

4. Results

The estimated parameters that best reproduce the data for our planet forming disk candidates are listed in Table 2 while the corresponding SEDs are shown in Figure 1. These fits have reduced $\chi^2 = 0.9 - 10$, i.e. the $\chi^2$ considering only the observational data point errors, and divided by the number of degrees of freedom. The disk masses obtained are within a factor $\sim 2$ from the rough estimates from Paper I, which were based on a single (sub)millimeter flux. We find $H_{100} \lesssim 2 - 6$ AU in all four cases, with estimated uncertainties $\lesssim 1.5$ AU. The comparison between the dust scale heights to the scale heights of the gas, which is in hydrostatic equilibrium, give a settling ratio $0.13 - 0.25$. Specifically for Tran 32 we get a rather flat geometry, with the smallest $H_{100}$ in our sample. This disk presents also the largest cavity and is bright enough to be detected by SMA extended configuration. A simultaneous SED + image fit will be presented in a future paper.

To test our results against an alternative model, we have used the precomputed grid of SEDs by Robitaille et al. (2007). A cavity is also inferred in all 4 cases, with $R_{\text{cav}} \sim 4 \sim 38$ AU, as well as some dust settling leading to flat geometries ($H_{100} \lesssim 4$ AU). However, the on-line fitting tool fails to accurately reproduce the SED for 2 of our targets, Tran 11 and 32. A discussion on the preferential use of RADMC to model transitional disks and comments on alternative observational characterization of them can be found in Merín et al. (2010).

5. Discussion

Extensive work in non-linear model fitting have been applied in many areas, and recently to disk modeling by Isella et al. (2009). They have used the two layer approximation of Chiang & Goldreich (1997), whereas we compute the thermal structures with significant detail using the RADMC code. In this study we have followed the literature by Andrews et al. (same parametric model and opacities) who have performed refined grid searches over 8 parameters. Their acute comments on the technical obstacles (Andrews et al. 2011) and non-uniqueness of the fit, also apply for our approach.

We have estimated some of the physical parameters describing the dust structures of 4 transition disk systems that are excellent candidates for ongoing giant planet formation. The cavities sizes inferred for our targets, $R_{\text{cav}} \sim 2 - 8$ AU, are in agreement with the distribution of semi-major axis of exoplanets, which has a bi-modal behavior, peaking at $\sim 0.05$ and $2$ AU and extending up to $\sim 10$ AU (exoplanets database, http://exoplanets.org). The mass of the disks and the actual size of their inner holes depend on the assumed opacities. The small scale height of the dust in all our targets suggest this could be a characteristic property of planet forming disks. This is an intriguing results that

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Table 1. Target Properties

| Name$^a$ | Spitzer ID | SpT | $T_{\text{eff}}$ (K) | $L_*$ ($L_\odot$) | $R_*$ ($R_\odot$) | $M_*^2$ ($M_\odot$) | Age (Myr) | $A_V$ (mag) | $\log M_{\text{acc}}^2$ ($M_\odot$/yr) | $\lambda_{\text{H}_2\text{O-off}}$ (um) | $\delta_{\text{excess}}$ | $M_{\text{disk}}^d$ (M$_{\text{JUP}}$) |
|----------|------------|-----|-------------------|-----------------|-----------------|-----------------|----------|----------|------------------|-----------------|-------------|-----------------|
| Tran 11  | J162506.9-235050 | M3  | 3470 0.24 1.25    | 0.3             | 2.1             | 3.8             | -8.8    | 8.0       | 0.65             | <1.5            | 1.3         |                 |
| Tran 21  | J162854.1-244744 | M2  | 3580 0.51 1.74    | 0.4             | 4.1             | 5.0             | -7.3    | 8.0       | 0.30             | <1.3            | 1.1         |                 |
| Tran 31  | J163205.5-250236 | M2  | 3580 0.19 1.08    | 0.4             | 4.1             | 5.0             | -7.3    | 8.0       | 0.30             | <1.3            | 1.1         |                 |
| Tran 32  | J163355.6-244205 | K7  | 4000 0.78 1.70    | 0.7             | 4.1             | 5.0             | -7.3    | 8.0       | 0.72             | 11.1            | 0.7         |                 |

$^a$ Alternative names: Tran 21 is WSB 63, Tran 31 is WSB 75, and Tran 32 is RXJ1154.9-2242. $^b$ Stellar parameters from pre-main sequence evolutionary tracks by Siess et al (2000). $^c$ Based on the velocity dispersion of the Hα line from Paper I. $^d$ Rough estimates of the disk masses based on a single (sub)millimeter flux or upper limits from Paper I.

Table 2. Model parameters

| # | $M_{\text{disk}}$ ($M_{\text{JUP}}$) | $H_{100}$ (AU) | $R_{\text{cav}}$ (AU) | $\log \delta_{\text{cav}}$ (dex) |
|---|------------------|--------|-----------------|-----------------|
| 11 | $<2.0 \pm 0.7$ | $<4.2 \pm 1.3$ | 4.8 $\pm 2.5$ | $\lesssim -6.2$ |
| 21 | $0.6 \pm 0.2$ | $3.1 \pm 0.8$ | $1.9 \pm 0.3$ | $-4.9 \pm 0.8$ |
| 31 | $<1.7 \pm 0.1$ | $<1.9 \pm 0.1$ | $1.5 \pm 0.4$ | $-5.2 \pm 0.5$ |
| 32 | $17.0 \pm 5.3$ | $2.0 \pm 0.5$ | $7.9 \pm 2.3$ | $\lesssim -6.3$ |

$^a$ $M_{\text{disk}}$ are upper limits for Tran 11 and 31 as their 1.3 mm fluxes are also upper limits. $^b$ $H_{100}$ is an upper limit for Tran 31 as its 70 $\mu$m fluxes is also an upper limit.

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Note that there is no guarantee that the marginal distribution is Gaussian so the dispersion of the sample can only be a rough indicator of the probable error as in Isella et al (2009).
The disk masses obtained here cover a rather wide range of masses, from $\sim 0.6 M_{\text{JUP}}$ to $\sim 17 M_{\text{JUP}}$ that extends to lower values the mass range obtained by Andrews et al., i.e. $5 - 42 M_{\text{JUP}}$ for systems that have been modeled in the same way, i.e. with same parameterizations and opacity tables. However, Andrews et al. (2009, 2010a) fitted their systems with larger values of the depletion factor, $\delta_{\text{av}} \sim 10^{-4} - 10^{-2}$, and obtain larger cavities, $R_{\text{cav}} = 20 - 40$ AU. We note that in Andrews et al. (2011) where the model include a more complex surface density profile (i.e. with an inner disk inside the cavity) the range of masses estimated for 12 disks with resolved images is $\sim 8 - 128 M_{\text{JUP}}$ but comparisons could be misleading in this case. Some differences are probably the result of a selection effect. While Andrews et al. selected their targets based on large (sub)millimeter fluxes, our selection criterion is based on the slope of IR SEDs, and the presence of accretion.

At a southern declination of $\sim 25$ deg and a distance of $\sim 125$ pc, our targets are excellent targets for follow up studies with Herschel and the Atacama Large Millimeter Array (ALMA) to investigate their properties in more detail, and in particular, the small holed transition disks will require its better spatial resolution. Herschel far-IR photometry would bridge the gap between the mid-IR and the (sub)mm wavelengths accessible from the ground and help to better constrain the scale heights and the flaring angles of the disks. Herschel spectroscopy of line structure lines, such as the 63.2 $\mu$m [O I] line, could help to probe their gas content and hence the gas to dust mass ratio. Similarly, resolved images with ALMA will break some of the degeneracies of the models and will allow to better understand the physical properties of these fascinating disks, thereby helping to elucidate the conditions in which planets are formed.

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Fig. 1. Best fit SEDs (solid lines) obtained using RADMC, in the context of a flared disk model with an inner cavity. The dashed line shows the input stellar model atmosphere. The filled circles are extinction corrected values, while the arrows are upper limits.