Probing the Disk Structure of the Older Classical T Tauri Star, PDS 66

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Abstract: We combine our new millimeter interferometry data from the Australia Telescope Compact Array (ATCA) with existing data for the old (~17Myr[a]), nearby (86pc) classical T Tauri star (CTTs), PDS 66. This extensive data set will be used to constrain physical models of the spectral energy distribution (SED) using the CGPLUS code described by Dullemond et al., 2001. The best-fit parameters will describe the structure of the circumstellar disk, and lead us to a better understanding of grain growth (and planet formation) timescales, and disk evolution in general. Our goals are (1) to determine the grain size distribution, and (2) to place a limit on the outer disk radius and compare that to what is expected from viscous disk spreading. We find evidence of grain growth from a preliminary analysis of the mm-wave data. This project is part of the Spitzer Legacy Program 'Formation and Evolution of Planetary Systems' (FEPS).

Introduction

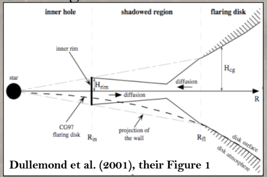
PDS 66 is a classical T Tauri star (CTTs) in Lower Centaurus Crux, a subgroup of the Sco Cen OB association (Mamajek et al., 2002), shown in the image below. While the typical CTTs stage is thought to last only 3 Myr, PDS 66 is still actively accreting and has an estimated age of about 17 Myr[a]. Such an evolved star with an SED characteristic of an optically thick disk (Silverstone et al., 2006) makes an interesting laboratory for studying the disk structure. The first steps of planet formation require growing micron-sized grains into cm-sized grains (e.g. Wilner et al., 2005). The slope of the long-wavelength spectrum is a sensitive probe of the grain size in a circumstellar disk, because the flux in the Rayleigh-Jeans limit is proportional to the mass opacity coefficient κ_ν (see Figure 1).

Observations & Reductions

The SED is composed of data from several instruments, taken at different times. The U,B,V,R_c,I_c photometry are taken from Batalha et al., 1998. We use 2MASS J,H,K photometry, and IRAS 12 and 25 μm photometry. Mid- to far-infrared data were obtained and reduced by the FEPS team using all three instruments aboard Spitzer: IRAC, MIPS, and IRS (Meyer et al., 2006 and references therein). The 1.2 mm observation comes from the Swedish-ESO Submillimeter Telescope, and is described in Carpenter et al., 2005. The most recent addition includes observations at 3mm, 12mm, 3cm, and 6cm , which were taken with ATCA and processed with the MIRIAD package (Sault et al., 2005). The measured fluxes for 3 and 12mm are 22.0 and 0.41 mJy, respectively. The internal and calibration uncertainties are approximately 20%. The 3mm data provide the maximum spatial resolution: 3.5" or 300 AU at the distance of PDS 66. Unfortunately, we did not resolve the disk.

Method and Parameter Estimation

We use CGPLUS (Dullemond et al., 2001) to model the irradiated circumstellar disk, which includes contributions from the star, inner rim, surface layer, and midplane (see the image below). We use a three-dimensional grid defined by the outer disk radius, the disk mass, and the surface density power-law and estimate the best-fit from the minimum χ^2. The surface density power-law, p, is defined such that $\Sigma=\Sigma_o(r/r_o)^{-p}$. The fixed model parameters are listed in Table 1 and the free parameters are listed Table 2. The range for the disk mass is determined by using a high gravitational instability criterion of $M_{disk}/M_{star}=0.25$; and the lower limit is set by α-disk theory using the mass accretion rate ($10^{-8.3}$ M_{sun}/yr) to derive the average surface density of the disk, leading to the lower limit on the disk mass. We set the ranges for p and R_{disk} to reasonable estimates. The grain size used by the model can also vary. We start out with 0.1 μm grains (Figure 2, left), and find that we need to incorporate larger grains to obtain a better fit at longer wavelengths (Figure 2, right).



Dullemond et al. (2001), their Figure 1

Table 1: Fixed Model Parameters

M_{star}	1.3 M_{sun}	distance	86 pc
T_{star}	5228 K	$T_{dust\ sub}$	1400K
L_{star}	1.2 L_{sun}	inclination	45°

Table 2: Free Model Parameters

p	0 - 2
R_{disk}	30 - 1000 AU
$M_{disk}{}^{b}$	10^{-5} - 0.3 M_{sun}

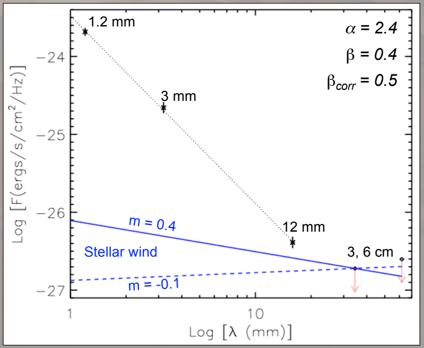


Figure 1: Preliminary Grain Growth! Long-wavelength spectrum showing the fit to the data points (dotted black line). At these wavelengths, the flux from a blackbody goes as ν^2; and if the disk material is optically thin, the flux is also proportional to the mass opacity, $\kappa_\nu \propto \nu^\beta$. Therefore, $F_\nu \propto \nu^{2+\beta}$, and we can derive β from the observed slope. For grain sizes << λ (ISM-like grains), β→2; and for grain sizes >> λ (blackbody), β→0. Here, we measure a slope of -2.4, which corresponds to a β of 0.4 thus indicating grain-growth from the initial ISM grains. β has been corrected for optically thick emission, using values for the temperature and density power-laws such that the correction is maximized. We find β_{corr}~0.5. There was no detection at 3/6 cm, so we conclude that the effects of stellar wind are insignificant.

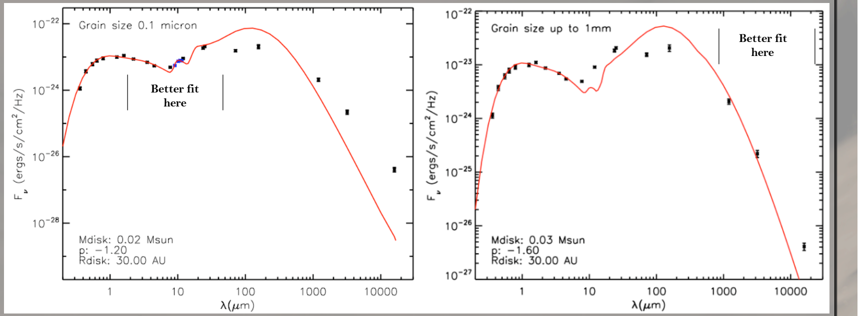


Figure 2: SED With Best Fit Models. The best fit models (red) are determined from the minimum χ^2 calculated between K-band to 25 μm (left) and 1.2mm to 12mm (right). The 0.1 μm grains (left) fit the mid-IR region of the SED, where we expect smaller grains to dominate the emission, but they do not fit well at longer wavelengths. We are exploring different grain sizes, and find a better fits to the long wavelength SED using grain sizes ranging from 0.1 μm to 1mm, assuming a power-law distibution of grain sizes where n(a) ~ $a^{-3.5}$ (right). Since the larger grains cannot provide a good fit in the mid-IR, we expect to use a combination of grain sizes to better model the data.

Conclusions & Future Work

Bouwman et al., 2007 give a detailed analysis of the low-resolution IRS spectrum for PDS 66, and they find evidence for grain sizes up to 5 μm. Our estimate of β in Figure 1 and the model fits in Figure 2 indicate that we need grains larger than 5 μm to fit the mm points. We expect that we will need to use smaller grains as well to fit the data in the mid-IR. Since we did not resolve the disk, the models will be degenerate in the disk mass, radius, and surface density profile. Therefore, it will be necessary to utilize possible observational constraints so that we can rule-out models. One way to do this will be to limit the disk radius to that observed from scattered light images obtained from HST. Another constraint on the disk radius may come from limits to the surface brightness at large radii from the mm-wave interferometry. It will be interesting to compare the best-fit outer disk radius to the radius expected from viscous disk spreading. The maximum grain size that best fits the SED together with the age of the star will be useful in placing limits on the timescales for grain growth, and thus planet formation.

References

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[a] The age of PDS 66 may be closer to 12 Myr (E. Mamajek, private communication)

[b] M_{disk} is the total (dust+gas) disk mass, and we assume a gas-to-dust ratio of 100