Probing Dust Settling in Proto-planetary Disks with ALMA

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Abstract. Investigating the dynamical evolution of dust grains in proto-planetary disks is a key issue to understand how planets should form. We identify under which conditions dust settling can be constrained by high angular resolution ALMA observations at mm wavelengths, and which observational strategies are suited for such studies .We find out that an angular resolution better than or equal to » 0.1" (using 2.3 km baselines at 0.8mm) allows us to constrain the dust scale height and flaring index with sufficient precision to unambiguously distinguish between settled and non-settled disks, provided the inclination is close enough to edge-on ($i > 75°$). Ignoring dust settling and assuming hydrostatic equilibrium when analyzing such disks bias the derived dust temperature, the radial dependency of the dust emissivity index and the surface density distribution.

1 Introduction

Grain growth and dust settling are two key ingredients in the planets formation process. Settling will speed up the growth process by favouring grain collisions, firstly by increasing the relative vertical velocities, as settling acts differently in function of the dust dynamic properties [1], and secondly by concentrating dust close to the midplane. On top of that, a high dust to gas ratio in this area, can affect the gravitational stability and control the initial step of the formation of planetesimals [2]. Contrary to other shortest wavelenghts, the moderate opacity of the mm/submm domain allows dust mass estimate and should accordingly probe material throughout the complete disk structure. In this paper, we then study the impact of dust settling on the disk imaging at mm wavelengths, in order to define adequate observational strategies to constrain this phenomenon with ALMA.

2 Methods

We investigate here potential way to distinguish *any* settled disk from *any* non-settled one. Our approach is to analyze simulated images of settled disks with non-settled, homogeneous disk models. Under this approach, settled disks may result in very unusual parameters which cannot be ascribed

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Table 1. Disk physical parameters for a 1 solar mass.

Physical characteristics	Adopted values
type of grains	Moderate (≤ 3 mm) or Large (≤ 10 cm)
gas scale height	Hydrostatic Equilibrium
Averaged Gas/Dust	100
Kinetic and Dust Temperature	$T_k(r) = 30 \left(\frac{r}{R_0} \right)^{-0.4}$ Kelvin
Reference and Inner radius	$R_0 = 100$ AU and $R_{int} = 3$ AU
Truncated disk	
Gas Surface Density (g.cm^{-2})	$4.35 \left(\frac{r}{R_0} \right)^{-1}$ with $R_{out} = 100$ AU
Tapered disk	
Gas Surface Density (g.cm^{-2})	$17.4 \left(\frac{r}{R_0} \right)^{-0.5} . exp\left((\frac{R}{R_c})^{1.5} \right)$ with $R_c = 50$ AU

to "normal" non-settled disks. For example, the dust scale height H_0 should be small, as well as the flaring index h, in comparison with the hydrostatic scale height.

2.1 Disk Description

The disks parameters are representative of the disks studied by [3] and are given in Table 1. The disks are in hydrostatic equilibrium with no vertical temperature gradient and orbit around a $1M_\odot$ star. In the truncated model, the gas surface density is a simple power law with sharp inner and outer radius. In the viscous model, the density is tapered by an exponential outer edge. Both models have the same total (gas+dust) disk mass is 0.03 solar mass. Each disk has been imaged at 4 inclination angles (90°, 85°, 80° and 70°).

2.2 Dust Properties

2.2.1 Dust emissivity

The dust emissivity as a function of frequency depends on the dust size distribution and grain composition. Given the important unknowns in the dust geometry and composition, we have elected to use a parametric method to model. Our dust emissivity model is based on two asymptotes: one at small wavelengths ($a \gg \lambda$) where the absorption coefficient is dictated by the geometrical cross section, and another at long wavelengths ($a \ll \lambda$) for which a power law applies. These two regimes are then connected by a resonance region near $\lambda = 2\pi a$, caracterized by its height and width.

The minimum grain size was 0.01 μm and the maximum grain size 3 mm for the moderate grain model or 10 cm for the large grain model. The dust size distribution was represented by a power law of index $p_d = 3$ and with the constant density $\rho_d = 1.5$ g.cm^{-3}. In the example presented in these proceedings, the parameters have been adjusted in order to match the dust properties used by [4].

2.2.2 Dust settling

For obtaining the dust settling, we decided to use an approximation based on the results of global numerical calculations derived from theoretical approaches [5] which take into account ideal MRI-induced MHD turbulence predictions [6, 7] as well as vertical stratification of dust and gas.

Table 2. Minimizations of a tapered settled disk by an homogeneous truncated one: moderate size grains

Disk Case & inclination	T_0 30	q 0.4	p	R_{out}	β_i 0.613	H_0 14.6	h 1.30	χ^2
Assuming dust non-settling								
70°	34.8 ± 0.07	0.319 ± 0.001	2.14 ± 0.002	103.0 ± 0.03	0.442 ± 0.001	(15.7)	(1.34)	1276606
80°	35.0 ± 0.07	0.346 ± 0.002	1.85 ± 0.004	103.0 ± 0.03	0.292 ± 0.001	(15.8)	(1.33)	1415333
85°	29.5 ± 0.13	0.504 ± 0.004	1.31 ± 0.006	109.0 ± 0.06	0.293 ± 0.003	(14.5)	(1.25)	1683039
90°	19.9 ± 0.26	0.542 ± 0.008	0.16 ± 0.01	109.6 ± 0.09	0.930 ± 0.006	(11.9)	(1.23)	1319208
Assuming dust settling								
70°	35.8 ± 0.1	0.306 ± 0.001	2.23 ± 0.002	106 ± 0.03	0.466 ± 0.001	13.4 ± 0.04	1.33 ± 0.005	1262191
80°	35.5 ± 0.06	0.306 ± 0.003	1.95 ± 0.005	109 ± 0.03	0.390 ± 0.001	7.7 ± 0.04	1.21 ± 0.008	1203651
85°	32.5 ± 0.06	0.351 ± 0.004	1.62 ± 0.008	119 ± 0.04	0.444 ± 0.002	3.0 ± 0.04	0.46 ± 0.01	1156239
90°	29.2 ± 0.13	0.294 ± 0.012	0.20 ± 0.01	113 ± 0.06	0.754 ± 0.076	4.0 ± 0.04	0.10 ± 0.02	1162383

Numbers between brackets [] indicate fixed parameters. Numbers between parentheses are derived from another parameter (H_0 from T_k and h from q under the hydrostatic equilibrium hypothesis). The second row indicates the expected values of the parameters.

The main factor controlling the degree of settling is the dimensionless product of the dust stopping time τ_s by the angular velocity. This product is proportional to the grain size. When $\Omega\tau \ll 1$, the dust particles are coupled to the gas. On the contrary, when $\Omega\tau \gg 1$ (case for large grains), the dust particles are decoupled from the gas and settle towards the midplane.

It is convenient to further approximate the effects of dust settling by relating the "settling factor" $s(a, r) = H_d(a, r)/H_g(a, r)$ to the settling parameter $\Omega\tau_0 = (\Omega\tau_s)(r, z = 0)$: We have adopted the following law, which matches the previous asymptotic results

$$
\begin{aligned}
s(a, r) &= 1 & \text{if} \quad \Omega\tau_0 < \omega_c \\
&= \left(\frac{\Omega\tau_0}{\omega_c}\right)^{-0.5} & \text{if} \quad \Omega\tau_0 > \omega_c
\end{aligned}
\tag{1}
$$

with $\omega_c = 6.5\,10^{-4}$ being equal to the viscosity parameter α, within a factor of order unity [8].

2.3 Disks Simulations

We used the ray-tracer of the radiative transfer code DISKFIT [9] to generate brightness distributions at different wavelengths. The simulated brightness distributions obtained from DISKFIT were then processed through the regularly upgraded ALMA simulator implemented in the GILDAS software package [10] in order to produce the visibilities.

As a first guess, we choose to simulate observations obtained using 50 antennas with a single antenna configuration, so that observations at different wavelengths can be performed nearly simultaneously. A maximum baseline length of 2.3 km was used and the observations were assumed to be around the transit. Pseudo-observations of settled disks, have been created at four different frequencies, 100, 230, 340 and 670 GHz. At the distance of the nearest star forming regions (140 pc for Taurus-Auriga), the corresponding linear resolutions are 42, 18, 12 and 6 AU.

3 Results

Attempting to represent a settled disk by non-settled ones introduces several inconsistencies which reveal the existence of dust settling, provided the inclination is high enough. Table 2 displays the results.

3.1 Deriving the Scale Height

If we assume we are in hydrostatic equilibrium and that the dust is not settled, this hypothesis leads to unusual results. When viewed edge-on, the derived temperature is to some extent forced towards

low values to better mimic the small disk thickness (~ 19 K instead of 30 K). Relaxing the non-settled hypothesis allows us to recover the input temperature profile. For the moderate grains models, we found at high inclinations a dust scale height of 3-4 AU and of 2-3 AU for the large grains. By comparaison to the gas scale height which is equal to about 14 AU, this discrepancy shows clearly the existence of the dust settling.

3.2 Impact of the Surface Density Profile

If the surface density law for the pseudo-observation between the pseudo-observation and the model is not exactly the same, the dust scale height is more difficult to derive at low inclination (i. e. < 75-80 degrees). This result indicates that at inclinations below $80°$, the recovered scale height is sensitive to the exact shape of the surface density distribution, and cannot in general be determined accurately. Moreover, settled disks actually appear "pinched" ($h < 1$) rather than flared ($h > 1$).

3.3 Others parameters

Although they can serve as secondary indicators and are sensitive to the dust settling at high inclination ($\geq 80°$), others parameters like the spectral index β, p, ... cannot serve as diagnostics.

3.4 Instrumental Effects:

Thermal noise was added to the simulated *uv* data (corresponding to 30 min of observations for each frequency). The resulting image noise (point source sensitivity) are 13 μJy at 100 GHz, 20 at 230 GHz, 30 at 340 GHz and 111 at 670 GHz and did not prevent us to observe the dust settling. Thermal noise is then not a serious limitation to measure dust settling.

However, the atmosphere induces path length variations which are only partially recovered by the calibration techniques anticipated for ALMA. We have then evaluated the impact of the atmospheric phase noise and found that it should be below about $40°$ to avoid smearing by limited seeing.

3.5 Impact of the various Wavelengths

The above studies show that all the impact of dust settling is only in the effective scale height. Then, if we know the gas structure from previous observations, only one frequency is necessary. The best frequency for our analysis, giving sufficient spatial resolution and low thermal and phase noise was 340 GHz. More generally, spatial resolutions lower than 1" (or 14 AU for the Taurus aurigae region), no longer have sufficient resolution for our propose.

Nevertheless, if the gas structure is unknown, we need at least two frequencies to derive the dust temperature by resolving the optically thick parts of the disk. With dust emissivity index radial gradients like found by [3] and predicted by simulations of [1], proper identification of an optically thick core region requires at least 3 frequencies.

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