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TOWARDS MEASURING DUST SETTLING IN PROTOPLANETARY DISKS

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Abstract. High resolution images of a few protoplanetary disks are available over a wide wavelength range, from the optical with HST, NIR with ground-based adaptive optics, to millimeter with long-baseline interferometers. Model fitting of these images have been usually restricted to one wavelength. Attempts to simultaneously fit all wavelengths with a single model indicate that the grain size distribution is probably more complex than the simple ISM one. In particular, a dependence of the maximum grain size with vertical distance above the disk midplane (vertical settling) appears to be needed.

In this contribution we present synthetic images that include more realistic vertical grain size distributions obtained from recent hydrodynamical (SPH) calculations. The calculations are three-dimensional, they include the effects of hydrodynamical forces and gas drag upon an evolving dusty gas disk. We briefly describe the numerical method. In particular, the SPH code provides vertical density profiles for the dust as a function of grain size. Radiative transfer is done with a 3D multiple scattering code to produce synthetic images in all four Stokes parameters.

Comparison with observations of a sample of resolved disks will help validate the hydrodynamical simulations and to constrain grain growth and evaporation processes in these disks, a crucial step towards understanding planet formation. Such a combination of hydrodynamical and radiative transfer calculations is needed to prepare observations with future instruments like Planet Finder or ALMA.

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1 Introduction

In protoplanetary discs, the dust distribution can be substantially different from the gaseous one, depending on the exact range of dust particle sizes. As the opacity is dominated by dust, scattered-light observations at a given wavelength only show the extent of the dust distribution for grains of the relevant (and limited) size.

In order to correctly understand the motions of dust and gas and to derive their distributions, one needs to take into account the mechanisms of settling and preferential radial migration of dust towards the central star. We use the Smoothed Particle Hydrodynamics (SPH) (Gingold & Monaghan 1977; Lucy 1977; Monaghan 1992) technique which approximates a fluid by a collection of particles to follow the behaviour of gas and dust.

In a second step, we apply a Monte-Carlo light scattering code using the previously computed density tables of dust grains to produce synthetic maps of the disk.

2 Hydrodynamics

2.1 Multi-Phase SPH

Our hydrodynamical code (Barrière-Fouchet et al. 2004) was developed starting from Murray's (1996) code. Gas and dust phases are represented by two distinct types of particles. Only gas particles feel a pressure force and are affected by viscosity. The gas-dust combination feel the drag force and also a mixed term seen in both the dust and gas particle momentum equations.

The drag force can take the form of Epstein, Stokes or turbulent drag. Epstein drag is appropriate for the gas mean free path found in protoplanetary disks outside about 1 AU.

When the only force acting on dust is drag, the equation of motion reads (in the case of Epstein drag)

$$\frac{\mathrm{d}\mathbf{v}_{\mathrm{d}}}{\mathrm{d}t} = -\frac{\mathbf{v}_{\mathrm{d}} - \mathbf{v}_{\mathrm{g}}}{t_{\mathrm{s}}}, \text{ with } t_{\mathrm{s}} = \frac{s\,\rho_{\mathrm{d}}}{C_{\mathrm{s}}\,\rho}, \tag{2.1}$$

where $\mathbf{v}_{\mathrm{d}}$ is the dust velocity, $\mathbf{v}_{\mathrm{g}}$ the gas one, t_{s} the stopping time, C_{s} is the local sound speed, s is the radius of the dust grains, ρ_{d} the intrinsic density of a dust grain (for silicates $\rho_{\mathrm{d}} \approx 1\ \mathrm{g\,cm^{-3}}$), and ρ the gas density if it were to fill the whole space. The corresponding SPH equations are given in Maddison (1998).

In the simulations we present here, the central star mass is $M_\star = 1.0\ M_\odot$, the gaseous disc mass $M_{\mathrm{disk}} = 0.01\ M_\star$ and the dusty disc mass $M_{\mathrm{dust}} = 0.01\ M_{\mathrm{disk}}$. The gaseous disc extends to ≈ 200 AU. The disc is locally isothermal with the following radial dependences for temperature: $T(R) \propto (R/100\ \mathrm{AU})^{-3/4}$ and sound-speed: $C_{\mathrm{s}}(R) = c_0(R/100\ \mathrm{AU})^{-3/8}$. The aspect ratio is $H/R = 0.1$ at 100 AU, and the SPH viscosity parameters are $\alpha_{\mathrm{SPH}} = 0.1$ and $\beta_{\mathrm{SPH}} = 0.0$.

2.2 Discussion

For large (10 m) and small (μm) dust sizes, the dust distribution is expected to stay close to the initial flared disk. Large grains (boulders) are weakly coupled to the gas, and if started in Keplerian motion, they will keep this motion. Conversely, tiny grains are so strongly coupled to the gas that they are essentially co-moving (on the timescales we are considering here).

The 0.1 mm to 10 cm interval is where all the (short timescale) interesting dynamics takes place with respect to planet formation and disk evolution. In the $r - z$ plot of figure 1, significant deviation from the initially flared disk occurs.

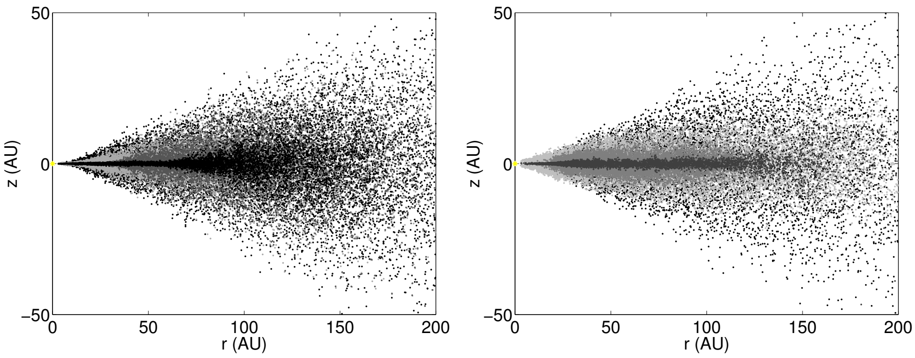

Fig. 1. Dust distributions in the meridian plane of the disk after 16 orbits at 100 AU. Left: gas (black), 10-m, 1-m and 10-cm size grains (light to dark gray). Right: gas (black), 100-μm, 1-mm, 1-cm size grains (light to dark gray).

3 Light Scattering

3.1 Light scattering as a diagnostic of dust settling

Light scattering is a powerful tool to infer dust grain properties in protoplanetary disks. Multiwavelength scattered light analysis can potentially be used to measure dust settling in these disks. Indeed, as the wavelength increases, the dust opacity decreases and the scattered light images probe deeper layers in the disks. Because we do not see the same part of the disk at different wavelengths, if dust settling has occurred in the disk, we will detect small grains at short wavelengths (*ie* in the upper layers) and larger grains at longer wavelengths (*ie* deeper in the disk) (Duchêne et al., 2004).

3.2 Numerical schemes

We use an improved version of the FOST (Ménard 1989, Dûchene 2000) Monte-Carlo light scattering code, with a dust grains size distribution varying with the position in the disk. This allows us to include dust settling : photons only see small grains in the upper layers of the disk (where the larger grains are removed), whereas they can scatter on bigger grains closer to the disk midplane.

3.3 First synthetic images

Figure 2 presents the very first maps obtained by the combined use of the SPH and light scattering codes.

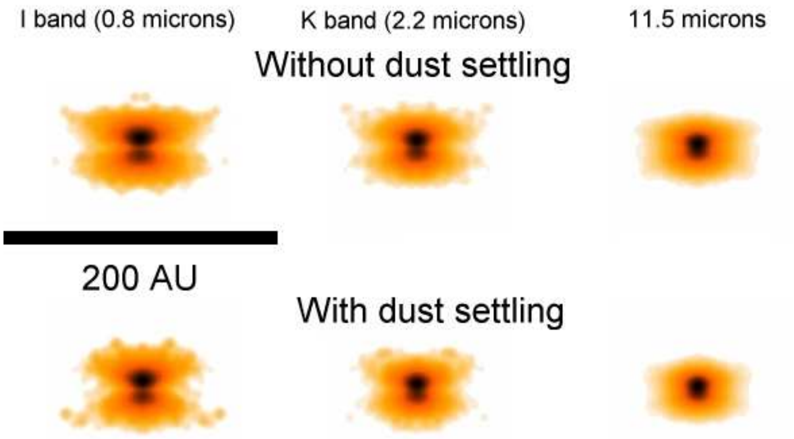

Fig. 2. Synthetic images of an edge-on disk, produced by the SPH and light scattering codes. With dust settling, the disk is smaller and the dark lane more pronounced.

The apparent size of the disk (and thickness of the dark lane) do not present the same variations with wavelength whether dust settling has occurred or not, showing that information about the dust settling can be derived from multiple wavelengths images.

These results are exploratory, a deeper analysis is underway. Dust distributions will be computed for a larger range of grain sizes ; grain coagulation and turbulence will be added in the SPH code. These synthetic images in scattered light and (soon) thermal emission will help to probe the dust sedimentation and full disk structure.

References

Barrière-Fouchet, L., Gonzalez, J.-F., Murray, J. R. 2004, A&A, submitted
Duchêne, G. 2000, PhD Thesis, Grenoble University
Duchêne, G., McCabe, C., Ghez, A. M., & Macintosh, B. A. 2004, ApJ, 606, 969
Gingold, R. A., & Monaghan, J. J. 1977, MNRAS, 181, 375
Lucy, L. B. 1977, AJ, 82, 1013
Maddison, S. T. 1998, PhD Thesis, Monash University
Ménard, F. 1989, PhD Thesis, Montreal University
Monaghan, J. J. 1992, ARA&A, 30, 543
Murray, J. 1996, MNRAS, 279, 402