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# Evolution of solids in planet forming disks: The interplay of experiments, simulations, and observations

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**Abstract.** Circumstellar dust analogues can be studied experimentally to determine their collisional behavior and their optical properties. These results affect simulations of circumstellar disks in various, substantial ways: Collision results determine how dust aggregates grow and how their aerodynamic properties change with time. This determines how solids move throughout the disk, how they accumulate, and how planetesimals might be formed. The optical properties determine the observational signature of these effects and allow us to constrain the spatial distribution of dust in disks, the sizes of the aggregates, as well as the temperature and optical depth of the dust emission. In this contribution, it is discussed how theoretical models and their predictions depend on laboratory results and what we learned about disks from high spatial resolution radio interferometry.

**Keywords.** planetary systems: protoplanetary disks — circumstellar matter — scattering — submillimeter

## 1. Introduction

Recent years have seen tremendous progress in the imaging of planet forming disks mainly thanks to the Atacama Large mm/sub-mm Array (ALMA) and to the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) that have delivered high resolution (of the order of 30 milliarcseconds) and high sensitivity imaging at (sub-)mm wavelength and in scattered light. Disk substructures appear to be ubiquitous at sub-mm wavelength showing mainly rings (Huang *et al.* 2018a) but also spiral structure (Huang *et al.* 2018b) and asymmetries (Andrews *et al.* 2018). While the millimeter emission appears to be mainly flat (Pinte *et al.* 2016, see also), scattered light observations show the disk surface to be strongly flared, as expected from previous modeling of the disk temperature and density structure (Avenhaus *et al.* 2018). At the same time, theoretical and numerical models of planet forming disks have advanced as well, allowing simulations of many orbits in 3D (e.g., Benítez-Llambay & Masset 2016), or including particle collisional evolution in 2D (Drążkowska et al., in prep.). Laboratory studies enter here at two crucial points: Firstly, collisional evolution of small dust particles depends sensitively on the outcome upon collision as determined from laboratory collision experiments (Blum & Wurm 2008; Güttler *et al.* 2010; Testi *et al.* 2014). Secondly, both interpretation of observations and predictions of observable signatures from theoretical models require detailed information on the optical properties of the solid material and how it relates to opacities and scattering phase functions, see Cuzzi *et al.* (2014), Kataoka *et al.* (2014), or Tazaki *et al.* (2016); Tazaki & Tanaka (2018) where public tools are now available, for example Birnstiel *et al.* (2018). In the following, I will show two examples to illustrate these points.

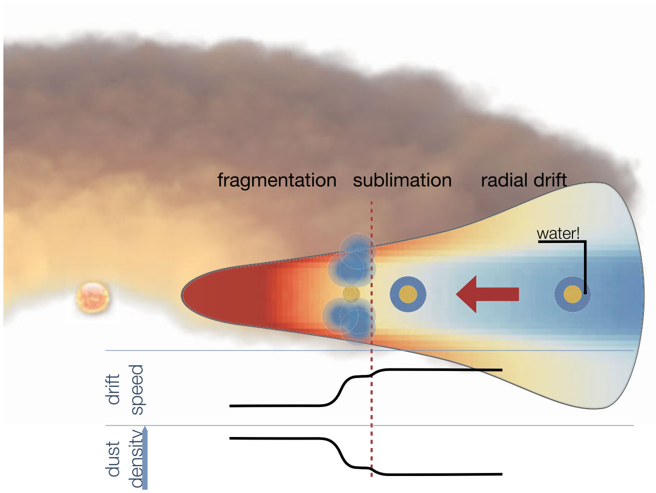


**Figure 1.** Schematical representation of the particle traffic jam at the water snow line.

## 2. Microphysics and transport of solids and volatiles

The water snow line, the zone where the temperature rises above the sublimation temperature of water, has attracted interest due to its importance for planet formation (e.g., Morbidelli *et al.* 2000), planetesimal formation (Kretke & Lin 2007; Brauer *et al.* 2008b; Drążkowska & Dullemond 2014), and its general importance for habitability. As models of particle growth and transport became majure (e.g., Brauer *et al.* 2008a), the importance of microphysical stability of the particles and their global redistribution was becoming clear. In Birnstiel *et al.* (2010), it was shown that the suspected change in the fragmentation threshold velocity of icy and dry particles can lead to a substantial traffic jam, increasing the dust-to-gas ratio inside the snow line by up to two orders of magnitude. The mechanism is shown in Figure 1: icy particles in the outer disk grow to sizes, at which radial drift (Whipple 1972; Nakagawa *et al.* 1986) becomes efficient. As the icy grains drift over the snow line, they lose their water. Even if this loss of volatiles leaves the particles intact, laboratory studies suggest, that dry material is substantially less sticky, leading to a significant reduction in the fragmentation threshold velocity $v_{\rm frag}$ from about $10\,{\rm m\,s^{-1}}$ to $1\,{\rm m\,s^{-1}}$. As the maximum particle size in the fragmentation limit (Birnstiel *et al.* 2012) is proporional to $v_{\rm frag}^2$, the particles can become up to 100 times smaller in radius. If radial drift is driving the grain radial velocity (for example if turbulence is weak), then this can lead to a drift speed reduction of up to a factor of 100. To sustain a constant dust accretion rate, the disk inside the water snow line needs to have a inversely scaled dust density as $\dot{M}_{\rm dust} = 2\pi\, r\, \Sigma_{\rm dust}\, v_r$, where $\Sigma_{\rm dust}$ and $v_r$ are the dust column density and dust radial velocity, respectively. This effect was shown to have significant observational consequences, that could be detected with ALMA (Banzatti *et al.* 2015) with a tentative detection seen in Cieza *et al.* (2016). Recent works have suggested that the position of the traffic jam might instead be outside the snow line if collective drift or a back-reaction of the dust to the gas dynamics is considered (Drążkowska *et al.* 2016; Schoonenberg & Ormel 2017), however the vertical stratification of these effects seems to bring the situation back to the original idea with the traffic jam inside the snow line (Garáte *et al.*, submitted). Either way this shows how fine changes in the surface energy of the monomers can lead to globally visible effects on the disk and along the way change the way planets may form and accrete their volatiles (e.g., Cridland *et al.* 2017).

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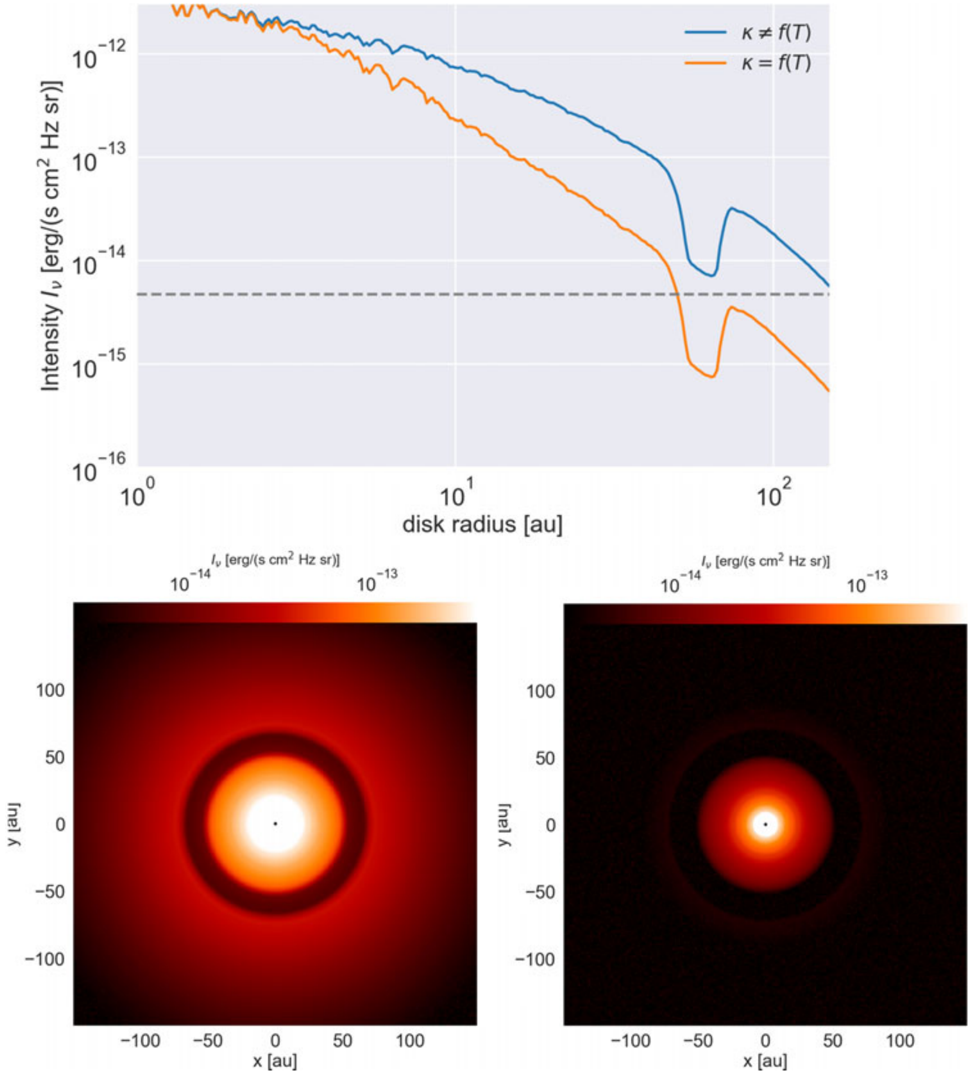


**Figure 2.** Sub-mm emission profile of a typical planet forming disk with a planetary gap. The blue line represents the radial intensity profile of the bottom left panel. The orange curve includes the temperature dependence according to Boudet *et al.* (2005), corresponding to the image in the lower right.

## 3. Temperature dependent opacities and disk masses

A realistic prediction of observable quantities does not only need to include the size distribution of the particles, but also their optical properties. While there has been a tremendous amount of literature on the subject, one aspect has gotten little attention: temperature dependence of the optical constants. There have been some earlier works from Boudet *et al.* (2005) and Coupeaud *et al.* (2011), and recently by Demyk *et al.* (2017a) and Demyk *et al.* (2017b). The results indicate, that in particular amorphous material shows a significant decrease in the long-wave (sub-mm and longer wavelengths) absorption opacity, in some cases up to an oder of magnitude. This opacity reduction becomes most pronounced below about 30 K, which applies to large parts of the entire mass reservoir of a typical protoplanetary disk. As a demonstration, Figure 2 shows the

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result of a radiative transfer calculation using RADMC-3D† with a typical set of optical properties and compares it to the expected reduction in emission for the same disk but assuming the temperature dependence from Boudet *et al.* (2005). It can be seen that the overall flux is reduced by the same amount, causing the disk mass to be underestimated by about a factor of 10 and possibly causes also an underestimation of the disk outer radius, depending on the noise level.

## 4. Summary

I have shown that laboratory measurements have a tremendous effect on models of planet forming disks in several ways. It was highlighted that the collisional properties affect the global appearance and global transport processes affecting planet formation and that opacities show a temperature dependence that can substantially change the emitted flux and therefore disk mass and size estimates. The combination of dynamical models and multi-wavelength observations might help up disentangle those effects in the future.

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