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Conclusions and outlook

The goal of this thesis has been to obtain a better understanding on the way dust coagulates during the first stages of planet formation. This requires to calculate the collisional evolution of the dust as a function of time. It is therefore natural to focus on the dust component, and treat the influence of the gas, *i.e.*, the gas-dust coupling, using analytical expressions. In this thesis the development of a detailed collision model is emphasized in particular, in which the collisional outcome depends on the properties of the colliding dust particles. The Monte Carlo method was instrumental in achieving this goal.

Because this thesis touches many diverse topics, I briefly emphasize a few of them individually and identify prospects for further work.

7.1 The Monte Carlo model

In chapter 2 we have introduced the Monte Carlo method and applied it to the upper layers of the protoplanetary disk. This approach was also used in chapter 4 for the evolution of chondrules in a dusty environment and in chapter 6 for the collisional evolution of dust in molecular clouds.

In all these cases the MC method merely reflects the particle-oriented approach, in which the state of the particle is characterized by a few parameters, *e.g.*, the porosity and mass in chapter 2 and chapter 6, and the mass fractions of the chondrule, compact dust, and porous dust components in chapter 4. This approach is therefore a middle course between the formalism followed by Kempf et al. (1999), where the position of each grain *within* an aggregate is stored, and the usual binning-methods. It is this compromise that makes our method so easily applicable, and allows us to connect to the finding of numerical or laboratory collision experiments; that is, the

output of these experiments can be converted to (a change in) particle properties as was seen, *e.g.*, in chapter 6.

The bottleneck of MC-methods are the $\sim N^2$ collision rates that must be continuously tracked during the evolution of the system. The consequence is that traditional MC-methods have difficulty to model broad distributions, where many simulation particles are required to follow both the low-mass particles (often dominating the numbers) and the large-mass particles (dominating the mass). Indeed, in chapters 2 and 3 the size distribution remained relatively narrow. However, fragmentation of dust will change this picture: a large dynamic range is then required. Therefore, in chapter 5 we have introduced a new method for MC-coagulation, the *grouping* method. In the grouping method, the numerous similar particles are considered collectively, like in the binning method. The key difference is that in MC the particles retain their individual behavior.

The grouping method described in chapter 5 is applicable to systems that experience runaway growth. An obvious application to extend this work is to apply the method to the planetesimal accretion stage of planet formation. Because of their gravitational focusing, planetesimals (km-size bodies and larger) have a collisional cross-section that scales with the $4/3$ power of mass. Thus, this phase is characterized by runaway growth, which cannot be modeled accurately by the usual binning approach (Wetherill 1990). Modeling this phase by a MC-method with its advantages in terms of the additional structural parameters may shed a new light on this key accumulation phase.

Perhaps the main drawback the MC-approach currently has, is that it is strictly 0-dimensional. The requirement, therefore, is that particles are distributed evenly throughout the volume, *i.e.*, there cannot be differentiation in position. For example, in chapter 4 we checked *a posteriori* whether the local assumption remained justified. However, there is no fundamental reason against including spatial information to the MC-particles — as long as their rate of interaction can be expressed in terms of probabilities. Another, more straightforward, approach is to ‘cut’ the system in several zones and calculate the collisional evolution separately in each of them. These are interesting avenues for further study.

7.2 The internal structure of particles

In this thesis MC-models are used as a tool to follow the internal structure of the particles. The most important structural parameter is probably the parameter that determines the porosity of particles, referred to as *enlargement* parameter in chapter 2 and *geometrical filling factor* in chapter 6. Thus, using this structural parameter the surface area-to-mass ratio is no longer confined to the $-1/3$ exponent as in the case of compact particles, which results in a very different velocity structure.

However, the most important property of the internal structure is that it affects the outcome of collisions. In this thesis we have related all collisional outcomes — sticking, bouncing, or fragmentation — to the internal structure of particles. Collisions are the key physical process that drive growth, and an understanding of planet formation is impossible without understanding individual collisions. Even in the

models in which the dust layer becomes gravitationally unstable at some point, it is still important to assess how collisions would affect the starting conditions (can particles grow to this size?) or the subsequent collapse phase. The theme of this work has been to connect the (microphysical) properties of dust particles to the outcome of collisions. In Chapters 2, 4, and 6 we have included results of numerical and laboratory findings. To connect the output of these experiments to the collisional evolution of physical systems will undoubtedly be the topic of many further studies.

7.3 Turbulence

Turbulence is arguably the most important mechanism to drive relative velocities between particles. Although the high gas densities in protoplanetary disk ensure a strong coupling ('strong' in astrophysical standards), which somewhat suppresses these velocities (and makes Brownian motion important for very small particles), as growth continues turbulence takes over. Furthermore, it mixes particles efficiently, both in the vertical as well as in the radial direction.

In chapter 3 relative velocities between particles in a turbulent velocity field were derived. It is a result that follows a long history. The framework of this approach—*i.e.*, the division of turbulent eddies into distinct classes—was already introduced by Völk et al. (1980), and improved by subsequent works (*e.g.*, Markiewicz et al. 1991; Cuzzi & Hogan 2003). By extending some of the simplifying assumptions in Cuzzi & Hogan (2003) the results of the Völk et al. (1980) study could now be put in closed form, at the level of $\sim 10\%$ in accuracy.

In future research this work may be expanded to treat an even more general approach, *e.g.*, by changing the spectrum of the turbulence other than Kolmogorov. Moreover, it is worthwhile to compare directly the results of this analytic work with hydrodynamical simulations of, *e.g.*, Carballido et al. (2008), who find a good correspondence. On the other hand, Johansen et al. (2007) find that velocities between particles at close distance are suppressed compared to the analytical expressions. Identifying the sources of this discrepancy and understanding the particle-gas interactions is important, in particular for models in which the dust component becomes gravitationally unstable.

7.4 The meter size barrier

Even were turbulence is unimportant, high particle velocities would still be present because of the intrinsically distinct nature of gas and dust (*e.g.*, Weidenschilling 1977a). This meter-size barrier—or, rather, the $St = 1$ barrier—is characterized by high, $\sim 10 \text{ m s}^{-1}$, relative velocities between dust particles. These relative velocities seem to be too high for particles to avoid fragmentation, and many works have subsequently focused on circumventing this barrier, either by producing local pressure gradients in the gas disk (Kretke & Lin 2007; Brauer et al. 2008b) or by studying the amount of particle concentration before they reach the $St = 1$ regime (Cuzzi et al. 2008). However, this thesis may offer some clues to 'revive' the idea to cross the $St = 1$ barrier by incremental growth. First, the impact of high velocities could

be remedied by mechanisms that dissipate the collision energy, *e.g.*, the particle's porosity. Second, if particles are fluffy, a sudden compaction (and corresponding increase in Stokes number) could help to cross this barrier. In chapter 4 some models came close to cross the $St = 1$ barrier, although the chondrule component did not contribute to the sticking capability and we did not include the collective effects that could have somewhat reduced particle velocities.

This idea is not new, of course. Cuzzi et al. (1993) have shown that if growth in the midplane regions is rapid, radial drift is not important. In the models of Weidenschilling (1997) growth also proceeded past the *m*-size barrier, despite the erosive processes that were included. However, Brauer et al. (2008a) using a "hard" fragmentation threshold of 10 m s^{-1} did not observe growth past $St = 1$. On the other hand, taking account of the internal structure, an array of new possibilities in terms of the collisional outcome becomes available (and the outcome is much harder to predict *a priori*). Therefore, it would be worthwhile to *simultaneously* model the internal structure, the location in the disk, and the growth of the particles and assess whether energy dissipation process can help to overcome the *m*-size barrier.

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