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7

Summary and outlook

The first step in the planet-formation process is the growth, through collision after collision, of microscopic dust grains into kilometer-size planetesimals. The goal of this thesis has been to achieve a better understanding of the microphysics that govern the collisional evolution of dust aggregates, and to understand not only how the physical structure of the growing aggregate is determined by its collisional history, but also how it influences the particle's future within the protoplanetary disk, and its chances of eventually growing into a planetesimal.

Here, I reiterate the main results of this thesis, and describe promising avenues for future research.

7.1 Collisions

Collisions are an important theme throughout this thesis: they help us understand the adhesive contact (Chapter 2); are the main drivers of dust evolution in protoplanetary disks (Chapters 4 and 5); and they are responsible for the production of small grains in debris disks (Chapter 6).

To understand and predict the behavior of aggregates in collisions, an intimate knowledge of the physical interaction between their microscopic constituents is required (see Sect. 1.3). By adding viscoelasticity and plastic deformation to the description of the adhesive contact, and comparing the theory to a collection of available experiments in the physics and astronomy literature, we have improved our knowledge of the forces governing head-on collisions (Chapter 2) and rolling motion (Chapter 3) of microscopic grains. These new force laws can readily be included in molecular dynamics simulations of macroscopic dust aggregates, themselves composed of large numbers of microspheres, to improve the collision model for aggregates.

Apart from silicates, experiments involving astronomically relevant materials (e.g., ices, organics, or mixtures of these materials) are scarce, and cover only a small part of the parameter space (grain size, aggregate porosity, etc.). Future experiments are necessary, not only to constrain the underlying physical model of Chapters 2 and 3, but also as a test for the molecular dynamics simulations of macroscopic aggregates.

7.2 Modeling coagulation

Simulating coagulation in protoplanetary disks is a challenging task, mainly because of the tremendous variety in particle sizes, collision velocities, and timescales that are involved. In this thesis, two very different numerical methods have been used to model the dust coagulation, each with their own advantages and disadvantages.

In Chapter 4, we employed a Monte Carlo (MC) technique to study coagulation locally, in a single vertical column of the protoplanetary disk. The MC method that was used is based on the distribution method of Ormel & Spaans (2008). The power of this approach is immediately clear from figures like Fig. 4.4: the method captures the complete mass distribution, even though at later times the smaller grains carry an insignificant amount of mass. This ability to resolve the full mass range is unique amongst Monte Carlo methods, and offers many possibilities for future research (see Sect. 4.6). The main disadvantages are that the model is local (though it treats the vertical direction in an integrated way), and that the simulations can slow down significantly when a steady-state is reached.

In Chapter 5, the semi-analytical model introduced in Sect. 4.5 is developed further to include the dust surface density evolution on a global scale. While this approach traces only the mass-dominating particles, it has the advantage of being very fast and flexible, while still capturing the essential features of the porous growth and radial drift processes. In principle, the method developed in Chapter 5 can readily be combined with more complex, time-dependent gas disk models, especially when the feedback of the dust onto the gas is small or dominated by the mass-dominating particles.

Understanding the aerodynamical properties of particles is very important when modeling their evolution. The coupling with the gas determines the collision velocity, but also the settling and radial drift behavior of the aggregate. In addition, compaction as a result of gas ram pressure can be an important mechanism to lower aggregate porosity. At the moment, the gas drag laws in the Epstein and Stokes regime are based on the assumption that the particles are compact and spherical (Whipple 1972). Future work is needed to test how accurate these drag laws are for highly-porous and irregular aggregates.

7.3 Growth barriers and planetesimal formation

The goal of this thesis has been to study how the microphysics influence the growth from grains to planetesimals, focussing in particular on their impact on several growth barriers (Sect. 1.2.3). It is clear that the microphysics are extremely important. For example, the bouncing barrier disappears when aggregates can grow highly porously (Wada et al. 2011; Seizinger & Kley 2013). At the same time, the difference in adhesive/elastic properties of ice versus silicate grains results in a factor of $\sim$10 increase in the fragmentation threshold velocity (Dominik & Tielens 1997; Wada et al. 2013). With bouncing and catastrophic fragmentation less relevant for porous ice aggregates, the major hurdle for growth is then rapid radial drift.

One possibility to circumvent the drift barrier is to grow very rapidly when Stokes numbers are around unity (Okuzumi et al. 2012). Such rapid growth is possible in a region behind the snow line (aggregates must be icy to avoid fragmentation) that can extend out to 20 AU for the most massive and dust-rich disks (Chapter 5). This planetesimal formation mechanism is an efficient process, and converts a large fraction of the available solid mass into planetesimals.

However, an important result of this thesis is that growth through the drift barrier can be frustrated by erosion: mass-loss as the result of high-velocity impacts with small projectiles (Chapter 4). When this occurs, conditions suitable for triggering streaming instability might be reached in weakly-turbulent and cold disks. The model of Chapter 5 can be used to pinpoint points in time and space where conditions for SI can be reached. The next step here would be to model the coagulation inside the formed clumps, while taking into account the feedback of the dust on the gas motions. Such models are needed to determine the efficiency of planetesimal formation through SI, and the properties (i.e., sizes, masses) of the formed bodies.

Chapter 5 shows two clear pathways to planetesimal formation in the region of the disk where ices are present: rapid growth through direct coagulation, and formation through streaming instability (SI). The next step would be to model the further evolution of the planetesimals formed through direct growth or SI, and compare the characteristics of the planets that form to the observed exoplanet population. To take this step, effects such as gravitational focussing, stirring by gas density fluctuations and pebble accretion have to be included (Johansen et al. 2014). The method developed in Chapter 5 can act as a starting point for such models, as it gives the locations and total mass of the formed planetesimals, as well as the radial flux and characteristics of material drifting in as a function of time.

7.4 Realistic disks and opacities of porous grains

The disk models employed throughout this thesis have been fairly simple, with the gas and temperature structure being described by power laws and the turbulence parametrized by a single and constant α. Moreover, the properties of the gas disk were assumed to be static in time, and were not influenced by the dust population. In reality, disks are more complex environments, and the properties of the turbulence will vary with location, depending on the mechanism that is driving it (e.g., Turner et al. 2014). Moreover, the strength of the turbulence can be influenced by the dust particle properties. For example, the abundance of small grains influences the ionization degree, important for MRI turbulence, while the presence of a dense midplane layer of decoupled dust particles can trigger Kelvin-

Helmholtz or streaming instability. The next generation of models will have to combine these effects in a self-consistent way.

Lastly, in this thesis we have focussed on the mechanical properties of porous grains and their ability to grow larger, but perhaps equally important is connecting coagulation models to observations of protoplanetary disks. The majority of current models for millimeter emission from protoplanetary disks assume compact dust particles, and directly relate the spectral index at these wavelengths to a dominating dust particle size (e.g., Testi et al. 2014). However, from the simulations in Chapters 4 and 5 it is evident that aggregates do not resemble compact grains anywhere in the disk. Moreover, studies focussing on optical properties of porous grains (e.g., Cuzzi et al. 2014; Kataoka et al. 2014), find that absorption and scattering properties at micrometer-millimeter wavelengths are profoundly affected by particle porosity. To fully appreciate the impact grain porosity has on the appearance of the dust population in protoplanetary disks, self-consistent porous coagulation models will have to be combined with porosity-dependent dust opacities. The models developed in this thesis are an important step in that direction.