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A Protoplanetesimal Dust Collision Model Based on Experiments

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1. Introduction

The formation of planets starts with the coagulation of small (sub-)millimeter sized dust particles in protoplanetary disks. Driven by their interaction with the surrounding gas, these particles collide at low velocities in the order of a few cm s^{-1} and stick at each other because of adhesive forces. This process leads to the formation of larger structures that are fractal at first. Due to the interaction with gas, the collision velocities rise, therefore the particles restructure and form compact but still very porous aggregates. Collisions among these particles do not necessarily lead to sticking. As these processes are not directly observable, our understanding of this first growth phase depends on theoretical models and experiments.

In the last years, the physics of collisions between dust agglomerates of different sizes, porosities and materials has been studied in many laboratory experiments [2]. To reach the low collision velocities, which required for a realistic simulation of protoplanetary-disk conditions, most of the experiments were conducted under microgravity conditions, like in the drop tower in Bremen or on parabolic flights.

The experiments have shown that the assumption that particles stick at each other for a wide velocity range and fragment if the velocity is sufficiently high enough, is not valid. In particular, we observed that collisions at intermediate velocities lead to bouncing.

2. Dust Collision Model

To make the results of the experiments accessible for theoretical approaches, we compiled them into a dust collision model [3]. The model predicts the outcome of a collision between two dust agglomerates, depending on the mass of the smaller aggregate, the collision velocity, the mass ratio of the projectiles, and the porosity. The latter two parameters are treated in a binary way: the dust aggregates are either similar or different sized (with a mass ratio >100) and either porous (porosity >60%) or compact (porosity <60%). Therefore, collisions can be divided in eight different regimes.

In general, the outcomes are sticking, bouncing, and fragmentation. Moreover, they are additionally divided in nine categories, which also regard more complex effects like the fragmentation of one particle accompanied by mass transfer to the collision partner. Figure 1 gives a simple overview of the collision outcome for similar sized porous particles. For a given collision velocity and mass (of the smaller particle) the colors indicate the growth (green), the fragmentation (red), as well as the bouncing and restructuring (yellow) of the collision partners.

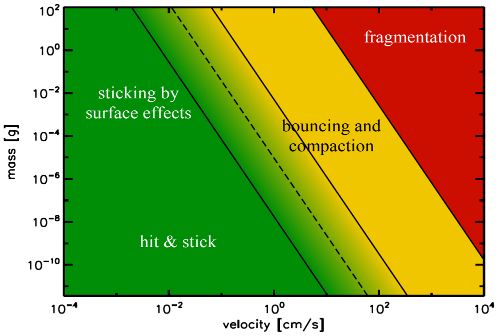

Figure 1: Parameter plot for similar sized porous particles. Green corresponds to areas where collisions lead to growth, yellow to bouncing and red to fragmentation. The transition regime is based on new experimental results.

3. New Experiments

After the original publication of the model new experiments have been conducted to improve our understanding of the influence of agglomerate properties like porosity, material, and temperature.

Many-Particle Collision Experiments

A large number of collisions are necessary to map the transition regime between sticking and bouncing. Generating so many collisions in a two-particle collision experiment is not feasible. Therefore, a new type of many-particle microgravity experiments was developed [c.f. abstract by Weidling et al., 5]. The experiments enable us to study a large number of collisions of an ensemble of particles in a shaken container. Based on experiments with different particle sizes, we found a transition regime between sticking and bouncing [Figure 1]. These experiments were performed with different dust materials to study their influence on the collisional outcome.

Fragmentation with Mass Transfer

The transfer of mass from an impacting dust agglomerate to a larger dust target seems to be a promising way to grow larger bodies. This effect has been studied in two experiments.

The first setup enables us to measure the transferred mass and its porosity to a target after multiple impacts of millimeter-sized projectiles. The experiment showed that the mass transfer increases whereas the porosity decreases with increasing impact velocity [4].

The second setup allows to study the mass transfer in collisions of two centimeter-sized agglomerates of different porosity. We found that in a certain velocity range, the more porous object breaks up and transfers mass to the remaining body. This mass transfer also increases with the impact velocity [1].

High-Temperature Experiments

All previous experiments have been performed at room temperature. Collisions in protoplanetary disks could occur at a wide temperature range, depending on their distance to the center star and due to episodic heating events.

To study the influence of the temperature on the outcome of a collision we developed a free fall experiment for heated dust agglomerates.

The agglomerates are positioned in a double-drop particle release mechanism. By dropping the upper agglomerate shortly before the lower one, the particles will gently collide. The sample holders are surrounded by a small oven that can be removed very rapidly before the release. This ensures the aimed particle temperatures at the time of collision.

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