Collisional evolution of many-particle systems in astrophysics

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Low-velocity collisions play a fundamental role in various astrophysical environments like protoplanetary disks (planet formation) or the Saturnian rings (e.g. dynamics and stability). These collisions are likely to occur at velocities in the cm s^{-1} range and below, and a satisfactory experimental realization of the lowest velocities is so far not possible even in microgravity environments like a parabolic flight aircraft or a drop tower facility. Moreover, many-particle effects can play an important role, e.g. for clustering (Miller and Luding [1]), which are ignored when only performing single particle-particle collisions. A perfect environment to perform the desired many-particle collision experiments is under microgravity condition with a microgravity time of few minutes, in which a particle system would be collisionally 'cooled' to velocities down to millimeters per second.

Previous collision experiments

The formation of planets starts with collisions between (sub-)micrometer sized dust particles, which stick and grow to larger aggregates. This process has been experimentally studied by Blum et al. [2], who performed a Space Shuttle experiment in which they dispersed micrometer-sized dust grains to a dense cloud and observed their evolution. This is an example for a many-particle collision experiment, which showed the efficiency of the initial growth of protoplanetary dust grains into small fractal aggregates consisting of many grains.

Their growth leads to larger, porous dust aggregates, which still collide but their sticking efficiency rapidly falls, such that various collisional outcomes (i.e. sticking, bouncing, or fragmentation) are possible, depending on collision parameters like mainly their collision velocity (see review by Blum and Wurm [5] and refs. therein). Most of the relevant collision experiments were performed at velocities of the order of one meter per second, i.e. bouncing collisions at 0.4 m s^{-1} (Heißelmann et al. [3]) or fragmenting collisions at 2 – 5 m s^{-1} (Lammel [4]) Examples are shown in Fig. 1. A new evolution model for protoplanetary dust aggregates (Zsom et al. [6]), based on these laboratory experiments compiled to a collision model by Güttler et al. [7], clearly identifies a lack of experiments at velocities of centimeters per second and below. At these velocities, it is still not clear whether aggregates stick to each other or just bounce like observed at velocities of 0.4 m s^{-1} [3], which is clearly one of the most fundamental questions to understand their growth.

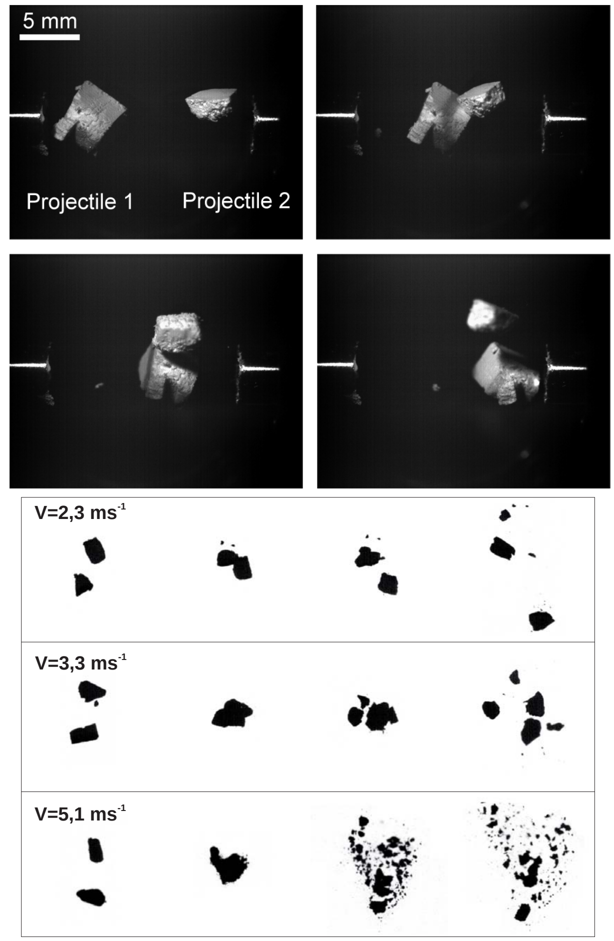

Figure 1: Collisions of millimeter-sized, porous dust aggregates typically lead to bouncing (top) or fragmentation (bottom), depending on the collision velocity. Courtesy: [3, 4].

Collisions at similar velocities are also important in the rings of Saturn: water ice particles in the size range between 1 cm and 10 m collide at velocities of typically less than 0.5 cm s^{-1}. Here, it is not expected that these particles stick to each other but bounce inelastically. The energy loss in these inelastic collisions strongly influence the evolution and the stability of Saturn's rings as an efficient process to dynamically 'cool' these. Heißelmann et al. [8] performed collision experiments between centimeter-sized water ice particles and found that the coefficient of restitution $\varepsilon = v_{\text{after}}/v_{\text{before}}$ can span a wide range from virtually 0 (completely inelastic) up to 0.8 (nearly elastic), being randomly distributed.

Moreover, Heißelmann et al. [8] performed a multi-particle experiment in the drop tower in Bremen, Germany, that showed the behavior of a system of about 100 glass beads with 1 cm diameter. The particles collided and lost about 60 % of their collisional energy in each collision, which leads to a mean velocity evolution following Haff's law, i.e.

$$v(t) = \frac{1}{\frac{1}{v_0} + (1-\varepsilon)n\sigma t},$$

where $v_0 = v(t=0)$ is the initial relative velocity, and n and σ are the number density and the collisional cross section of the glass spheres. After nine seconds of experiment time, they observed mean velocities as small as 0.4 cm s^{-1}, but also a strong deviation from the above law, which is most probably the onset of clustering.

Plans for future many-particle collision experiments

We are currently planning a new experiment in which we plan to observe the evolution of an ensemble of dust aggregates like in the experiment of Heißelmann et al. [8]. In contrast to Heißelmann et al., this experiment will be performed onboard a suborbital flight vehicle with 180 seconds microgravity duration (see abstract by Colwell, Blum & Durda). This has the advantage that we will not only observe many more collisions but that we will also be able to observe collisions far below the velocities of Heißelmann et al. Furthermore, this many-particle system will also allow us to observe collective effects (e.g. clustering) which have so far never been studied in dust aggregation experiments. The results of these experiments will directly go into the collision model by Güttler et al. [7] and the evolution simulation of dust aggregates under protoplanetary disk environments (Zsom et al. [6]). Additionally, sounding-rocket investigations of ensembles of centimeter-sized water-ice samples are planned to provide insight into the long-term collisional evolution of dissipative many-body systems like planetary rings.

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