Experiments on Fragmentation and Charge Separation in Pre-Planetary Dust Collisions

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Introduction

At the onset of the planet formation, single micrometer-sized dust particles collide at low velocities and immediately stick due to the van der Waals force (e.g. Weidenschilling & Cuzzi 1993, Blum 2004 and refs. therein). By this process, they form fractal dust agglomerates, grow in mass and are eventually restructured and compacted in further collisions (Dominik & Tielens 1997, Blum & Wurm 2000). At 1 AU this leads to the formation of centimeter- to decimeter-sized porous dust aggregates (Blum 2004), which may then collide with such high collision velocities that the collision does no longer result in mass gain of the larger aggregate. Contrawise, the smaller body will probably fragment and even the larger body will lose mass.

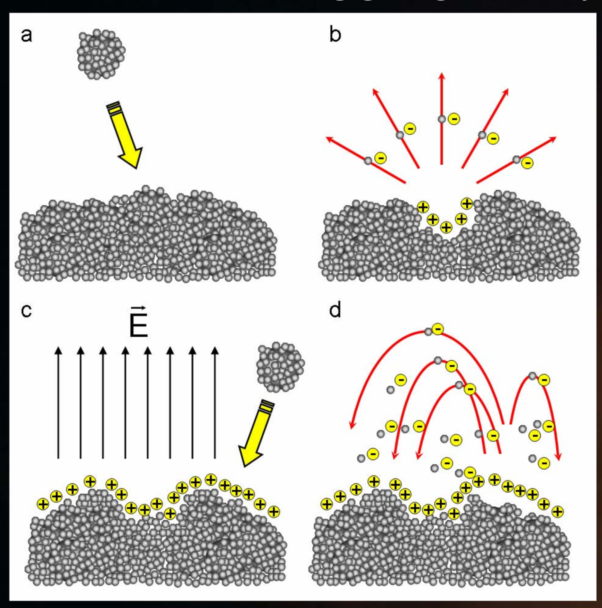

Fig. 1: One possible scenario for planetary growth of macroscopic bodies. Collisional charge separation leads to strong electric fields of the larger body, which may eventually reaccrete oppositely charged fragments.

One possibility to explain the further growth phase is collisional tribocharging with subsequent reaccretion (Fig. 1; Blum 2004): if the fragments of the smaller agglomerate (projectile) charge uniquely and oppositely to the larger aggregate (target; Fig. 1(b)), the target may establish a large electric field, following a number of collisions (Fig. 1(c)). This electric field may be strong enough to force charged fragments to reaccrete (Fig.1(d)).

Experimental Setup

The experiments are carried out in a vacuum chamber at an air pressure of $5 \cdot 10^{-4}$ mbar. Millimeter-sized, porous dust aggregates consisting of 1.5 µm SiO_2 spheres, are accelerated to velocities of up to 9 m/s and hit a solid target, where they fragment.

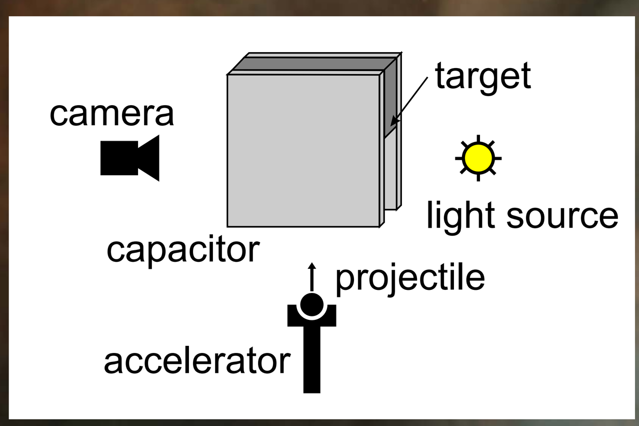

Fig. 2: Sketch of the experimental setup. A porous dust agglomerate is accelerated towards a solid target where it fragments. The collision is observed by a high-speed camera.

A high-speed camera (Fig. 2) observes this event in order to measure impact velocity and size of the projectile and the trajectories and sizes of the fragments. A capacitor with a strong electric field (e.g. 5 kV/cm) is installed to measure the charging of fragments from the deflection in the electric field.

Results 1: Fragmentation

The image series taken by the high-speed camera (Fig. 3) was binarized to measure the size of each fragment and to follow its trajectory. These trajectories were cleaned from gravitation and were linearly fitted (Fig. 3, bottom).

From the fitting parameters, the velocity and angular distribution of the fragments were calculated for six experiments, showing that most angles are very flat and fragment velocities within 20% of the impact velocity are most frequent.

The fragment sizes yield a mass distribution (Fig. 4, left) which follows a power law $n(m')=\alpha(m'/\mu)^{\alpha-2}$, where $\alpha \approx 0.8$ is the slope of the cumulative distribution (cf. Fig. 4, left, inset), m' is the normalized mass fraction, and $\mu \approx m'_{max}$ is the fitted mass fraction of the largest fragement, which represents the strength of fragmentation. Figure 4 (right) shows the decrease of the coefficient µ with increasing impact velocity. Thus, the size distribution is shifted to the left for higher velocities.

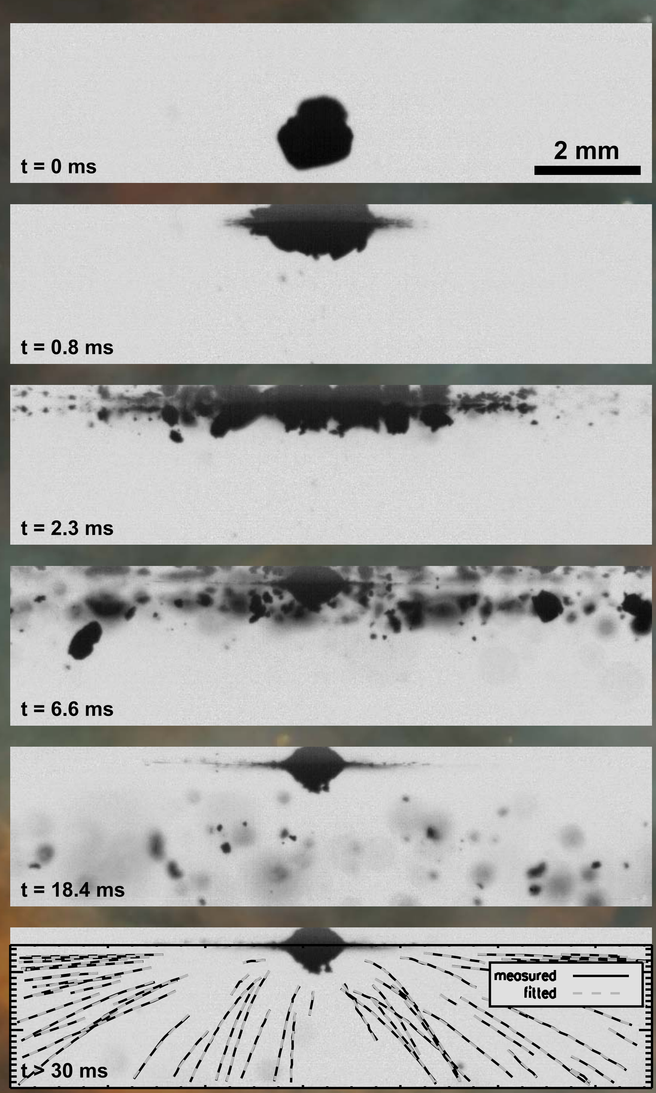

Fig. 3: Impact with a collision velocity of 3.5 m/s and a projectile mass of 9 mg. The trajectories for all fragments were measured, fitted and plotted into the last image.

The mass distribution $n(m)$ can also be translated into a size distribution $n(r)\sim r^{-3.6}$. For the fragmentation of $ZrSiO_4$ aggregates Blum and Münch (1993) found a similar behaviour with a size distribution $n(r)\sim r^{-3.4}$. Surprisingly, these exponents are in good agreement with the size distribution of interstellar dust grain (Mathis, Rumpl & Nordsieck, 1977) although the process of formation is widely different.

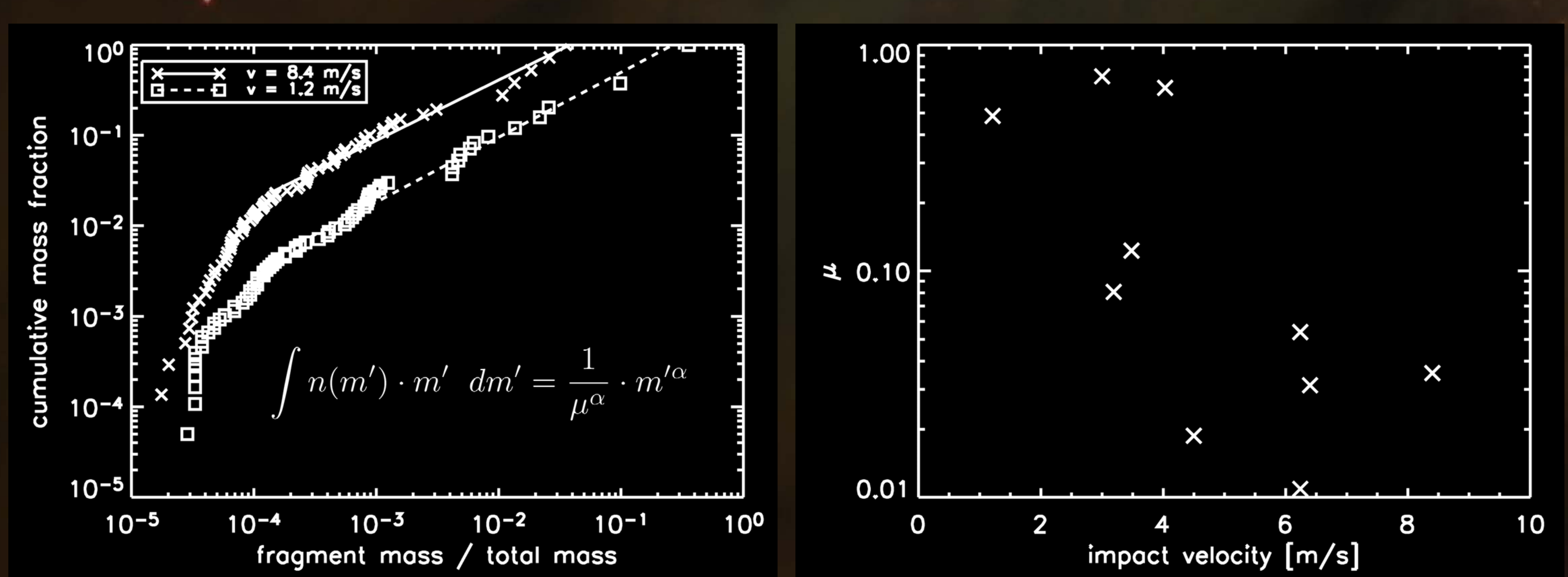

Fig. 4: (a) The cumulative mass distribution follows a power law $n(m')\cdot m'\cdot dm'=(m'/\mu)^{\alpha}$ where $\alpha \approx 0.8$ is virtually independent from impact velocity. **(b)** The prefactor µ (strength of fragmentation) of the mass distribution decreases for increasing impact velocity.

Results 2: Charge Separation

For an applied electric field, the fragments are accelerated in the horizontal direction (Fig. 5, bottom). Knowing the electric field and the mass of the fragments, the charge of each fragment can be deduced from a second order trajectory fit. In Fig. 6 the number of elementary charges (boxcar average) is plotted over the fragment mass and radius. As a simple analytical approximation we use

$$Q_{frag} = \pm 5 \cdot e_0 \cdot r\,[\mu m]^{2}$$

(dotted line). Negative charges slightly prevail in this experiment, which changes the prefactor and results in a net charge of the target. This is necessary for the reaccretion scenario but, still, this needs to be verified in forthcoming experiments. The quadratic radius behaviour of the charging gives evidence that the surface charge is constant, while Sternovsky et al. (2002) found a linear increase for a tribocharging process of colliding dust grains.

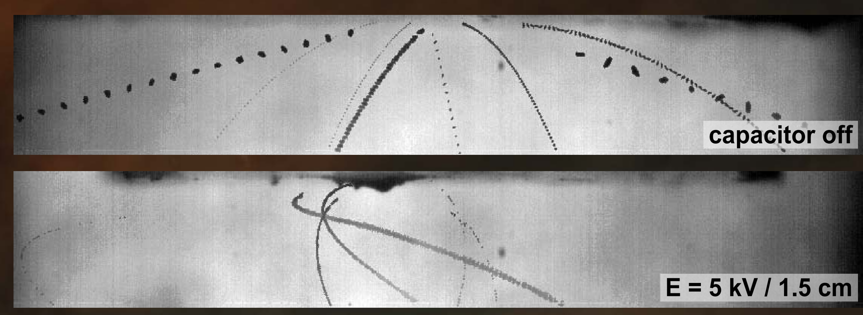

Fig. 5: Top: Examples for undisturbed trajectories (capacitor turned off). **Bottom:** Trajectories of charged fragments in an electric field of 5kV/1.5cm.

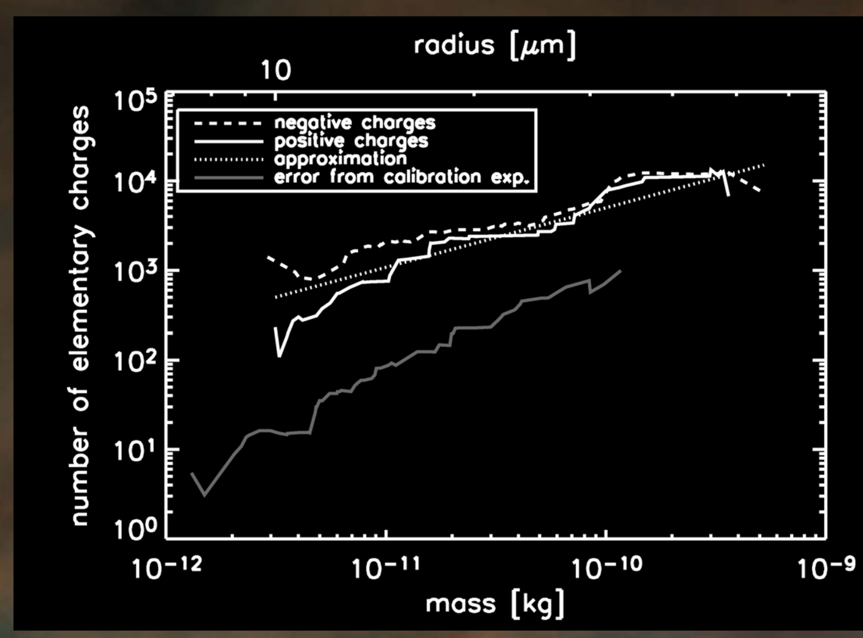

Fig. 6: Negative and positive charges per mass (white) and the measurement error (grey), which was obtained by a calibration experiment with turned off capacitor.

Application to Solar Nebula: Simulation of Reaccretion

Using the sizes, angles and velocities (Results 1) in a simulation of a gas flow around a decimeter-sized sphere (Stokes regime), the fragments' paths were calculated under solar nebula conditions. According to Weidenschilling & Cuzzi (1993) the impact velocity matches that of dm-sized target and a considerably smaller projectile at 1 AU in the solar nebula.

If no charging is assumed, no mass is reaccreted in the gas flow. Assuming a fragment charge of $5 \cdot e_0 \cdot r[\mu m]^2$ (Results 2), 0.4% to 17.8% of the total mass are reaccreted, depending on the charge accumulated by the target ($10^{11} e_0$ or $10^{13} e_0$, respectively).

It is questionable whether the target can accumulate a comparable charge in a sequence of collisions. Further studies need to be done.

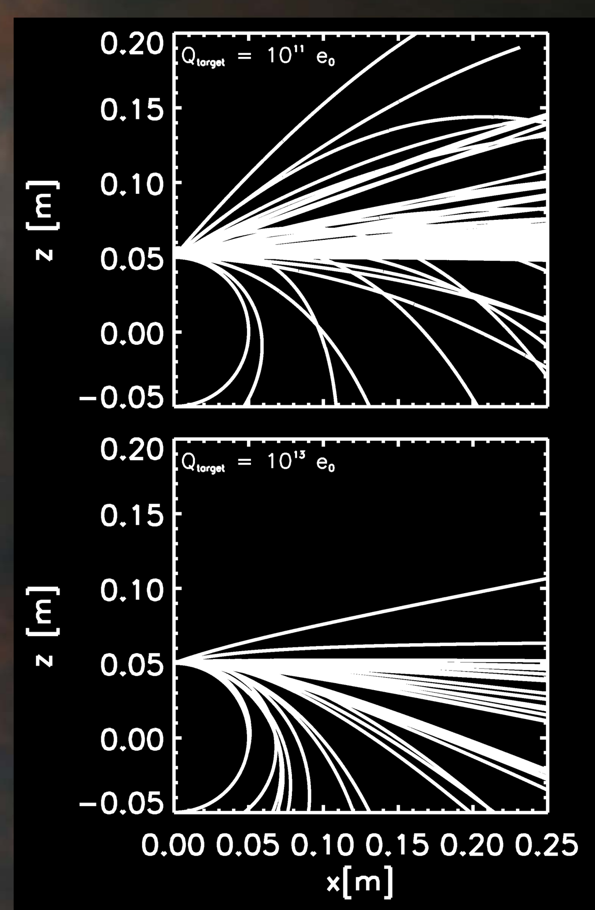

Fig. 7: Fragments from Fig. 3 in a solar nebula simulation to assess the efficiency of reaccretion by gas drag and Coulomb force.

Conclusion

Fragmentation is an important process in protoplanetary dust collisions and, in the first place, prevents further growth. Thus, a concise understanding of this process is necessary to open up potentially new ways of overcoming this growth barrier of which one way is the charge driven reaccretion. Therefore, laboratory dust collisions with velocities ranging from 1 to 9 m/s were performed, and the sizes, velocities, rebound angles and electric charging of the emerging fragments were measured.

The fragment sizes follow a power law distribution $n(r)\sim r^{-3.6}$ with a constant slope for all experiments. This exponent is well known from the size distribution of interstellar dust grains. Furthermore, charge measurements reveal a considerable fragment charge (up to ±10.000 e_0), which is proportional to the surface of the fragment. The trajectories in a solar nebula environment with gas drag and Coulomb force were determined and the raccretion efficiency can reach a few percent, depending on the charge accumulated by the target. Thorough measurements and calculations on this charging of the target will be performed in the future.

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