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EVOLUTION OF MACROSCOPIC DUST AGGLOMERATES – IMPLICATIONS FOR PLANETESIMAL GROWTH

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Abstract. The formation of preplanetary bodies is studied in laboratory experiments, especially the growth of decimeter bodies. As these macroscopic bodies are the building blocks for many growth models, it is very important to investigate possible formation processes and the mechanical properties of large dust agglomerates. Here, experimental results on the properties of decimeter-sized dust agglomerates and results of impact experiments at large collision velocities are presented. Fragmentation is a key process to growth at high velocities as energy is dissipated. Growth is observed for velocities up to 56 m/s and impact angles of up to 45°.

1 Introduction

The formation of planets and their km-sized precursors (so-called planetesimals) still offers many open questions. Especially the first growth steps from dust grains to large bodies is still poorly understood. In this phase the dynamics of solids are determined by the gas-particle coupling (Weidenschilling & Cuzzi 1993). It is out of question that small (μm) dust grains grow rapidly to dust aggregates of millimeter size, as the particle density is lare at the beginning and collision velocities in this regime are small (mm/s), while surface forces are strong enough to lead to sticking (Blum & Wurm 2008; Dullemond & Dominik 2005). Relative velocities between particles grow with increasing aggregate size, which leads to compaction of dust agglomerates (Weidling *et al.* 2009). Several studies show that compact dust agglomerates of equal (mm) size rather bounce of each other in mutual collisions than grow to larger sizes (Güttler *et al.* 2010; Zsom *et al.* 2010). This situation changes for particles of different sizes.

Further growth is possible if the size difference between the colliding bodies is large enough. In this case the smaller one is destroyed during the impact, which dissipates kinetic energy so some of its mass is transferred to the larger one (Teiser & Wurm 2009a; Wurm *et al.* 2005). Teiser & Wurm (2009a) showed that growth

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is possible for collision velocities of up to 56 m/s if the projectile size is small (0.5 mm). However, it is still debated if planetesimals can form by coagulation alone. Solid bodies in protoplanetary disks drift toward the central star due to gas drag at increasing velocities with growing particle size. Depending on the disk model these velocities can reach about 60 m/s (Brauer *et al.* 2008; Weidenschilling & Cuzzi 1993). Here, experiments on the mechanical properties and the collision behaviour of macroscopic dust agglomerates will be presented, to shed some light on this critical parameter range.

2 Experiments

To develop a self-consistent growth scenario two different experiments are performed. Both experiments are performed with the same dust material. The used material is quartz dust with a grain size distribution between 0.5 μm and 10 μm with 80% of the mass between 1 μm and 5 μm. This is in good agreement with grain sizes predicted for protoplanetary disks (Sicilia-Aguilar *et al.* 2011).

With the first experiment the mechanical properties of growing dust aggregates of decimeter size are determined by analysis of multiple collisions of small ($\sim$100 μm) dust agglomerates at collision velocities between 1.5 m/s and 7 m/s (Teiser *et al.* 2011). This is realized by sieving dust from varying drop height onto targets of different sizes (3 mm to 3 cm). This experiment simulates a larger (cm-size) agglomerate, which sweeps up small particles as it drifts through the disk. The collision velocities are then determined by the drift velocity, as the small particles are well coupled to the gas.

The second experiment is dedicated to analyze the further evolution of decimeter sized bodies. Here, the size range of the projectile is between 0.5 mm and 4 mm at collision velocities of 20 m/s and impact angles between 0° (central impact) and 45°. This is realized by accelerating (sub-) mm-sized dust agglomerates with a crossbow onto tilted dust targets (Teiser *et al.* 2011a). It was shown by Teiser & Wurm (2009a) that growth is possible at high collision velocities. They covered a wide velocity range, but only central collisions. The major focus of the experiments presented here is therefore the influence of the impact angle and the fragment size distribution.

3 Results

At collision velocities between 1.5 m/s and 7.7 m/s dust agglomerates grow by a combination of direct sticking and re-accretion. As large (decimeter) dust aggregates drift rapidly towards the central star, they are exposed to a strong head wind. Small particles couple well to the gas, which not only leads to large collision velocities. Impact ejecta are also exposed to this head wind, and are accelerated back to the target surface, as they are small and couple well to the gas. Therefore, re-accretion due to gas drag is an important process. It was shown that in laboratory experiments gravity is a good substitute for gas drag in protoplanetary disks,

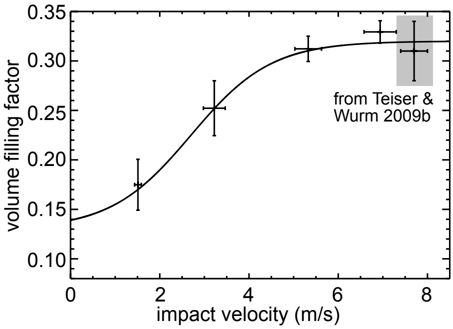

Fig. 1. Volume filling of growing dust agglomerates and its dependency on the collision velocity (Teiser *et al.* 2011).

as it leads to a constant acceleration of impact ejecta back to the target surface (Teiser & Wurm 2009b; Teiser *et al.* 2011). It was also shown that acceleration due to gravity in the laboratory is of the same order of magnitude as acceleration due to gas drag in protoplanetary disks. Experiments with targets of different sizes show that the properties of the resulting dust aggregates do not depend on the ratio between re-accretion and direct sticking, but only on the impact velocities. The resulting volume fillings are shown in Figure 1. The volume filling saturates for impact velocities larger than 6 m/s to a volume filling of 0.32 (porosity 68%).

For the second set of experiments projectiles and targets are made of compressed dust with a volume filling of 0.33 (targets) and 0.36 (projectiles). This is in good agreement with agglomerates forming by multiple collisions. At constant collision velocity and constant impact angle, erosion and growth occur depending on the projectile size. A critical projectile size for coagulation can be determined for each collision angle (Teiser *et al.* 2011a). This critical projectile size decreases linearly with increasing impact angle (Teiser *et al.* 2011a). In an earlier study it was shown that the critical projectile size also decreases with increasing impact velocity and is proportional to $1/v^2$ (Teiser & Wurm 2009a). Every collision above 10 m/s impact speed leads to fragmentation of the projectile (Wurm *et al.* 2005), even if the net effect is growth of the target. Figure 2 shows the size distribution of the impact ejecta (projectile and target fragments) for a collision velocity of 20 m/s. The fragment sizes are normalized to the original projectile sizes. The size distribution is generated by several experiments. This means that in one collisions only very few (one or two) fragments of the largest fragment sizes are generated. Except of the few largest fragments the size distribution can be described by a power law of the form $n = 9000 \cdot \mathrm{s}^{-2.1}$.

4 Discussion and conclusions

The porosity of macroscopic dust agglomerates does not depend on the detailed growth history, but has a universal value of 0.68 (0.32 volume filling). The experimental studies at large impact velocities are based on these values. They

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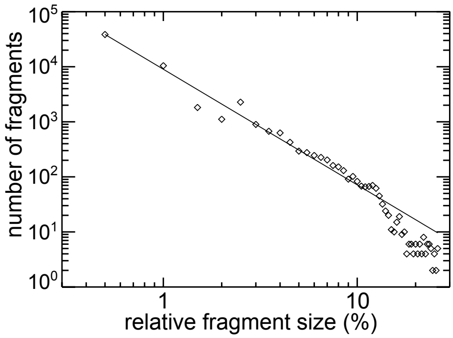

Fig. 2. Fragment size distribution for collisions at 20 m/s. The fragment sizes are normalized to the projectile size. The curve is a fitted power law with $n = 9000 \cdot s^{-2.1}$ (Teiser *et al.* 2011a).

show that growth is possible even at large collision velocities if the projectiles are small enough. The determined size distribution shows that in one collision a large amount of small fragments is formed. This is in rough agreement with the model by Geretshauser *et al.* (2011). Even if a collision leads to erosion, the formed fragments can be swept up by another large body moving through the same region within the protoplanetary disk. This leads to the conclusion that net growth to meter size and beyond might be possible by coagulation alone, if the combination of direct accretion, fragmentation and secondary accretion of the fragments happens on timescales which are short enough compared to a potential radial drift. However, these timescales are rather short, depending on the disk model (*e.g.* 100 years, according to Weidenschilling 1977). Additioanl processes like gravo-turbulent clustering (Johansen *et al.* 2007) might be necessary, if coagulation is not fast enough. To determnine coagulation timescales, a dedicated coagulation model is needed, which is beyond the scope of this article. However, we conclude that the experimental work provides critical input to such models which currently cannot be deduced otherwise.

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