Icarus 218 (2012) 688–700

Contents lists available at SciVerse ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Free collisions in a microgravity many-particle experiment. I. Dust aggregate sticking at low velocities

R. Weidling [a,*], C. Güttler [a,b], J. Blum [a]

[a] Institut für Geophysik und extraterrestrische Physik, Technische Universität zu Braunschweig, Mendelssohnstr. 3, D-38106 Braunschweig, Germany
[b] Department of Earth and Planetary Sciences, Kobe University, 1-1 Rokkodai-cho, Nada-ku, Kobe 657-8501, Japan

ARTICLE INFO

Article history:
Available online 14 October 2011

Keywords:
Planetary formation
Planetesimals
Experimental techniques
Collisional physics
Origin, Solar System

ABSTRACT

Over the past years the processes involved in the growth of planetesimals have extensively been studied in the laboratory. Based on these experiments, a dust-aggregate collision model was developed upon which computer simulations were based to evaluate how big protoplanetary dust aggregates can grow and to analyze which kinds of collisions are relevant in the solar nebula and are worth further studies in the laboratory. The sticking threshold velocity of millimeter-sized dust aggregates is one such critical value that have so far only theoretically been derived, as the relevant velocities could not be reached in the laboratory. We developed a microgravity experiment that allows us for the first time to study free collisions of mm-sized dust aggregates down to velocities of $\sim$0.1 cm s^{-1} to assess this part of the protoplanetary dust evolution model. Here, we present the results of 125 free collisions between dust aggregates of 0.5–2 mm diameter. Seven collisions with velocities between 0.2 and 3 cm s^{-1} led to sticking, suggesting a transition from perfect sticking to perfect bouncing with a certain sticking probability instead of a sharp velocity threshold. We developed a model to explain the physical processes involved in dust-aggregate sticking, derived dynamical material properties of the dust aggregates from the results of the collisions, and deduced the velocity below which dust aggregates always stick. For millimeter-sized porous dust aggregates this velocity is 8×10^{-5} m s^{-1}.

1. Introduction

The formation of planetesimals, the precursors of planets, is initiated by the collisional coagulation of small dust particles and aggregates. Velocities are induced from the interaction of these dust particles with the thin gas of the protoplanetary disk (PPD) and the gravitational interaction with the central star (Weidenschilling and Cuzzi, 1993). For the initially micrometer-sized dust grains, the collision velocities are small enough to let them stick to each other and form larger, fractal dust aggregates (Wurm and Blum, 1998; Blum et al., 2000; Blum and Wurm, 2000; Krause and Blum, 2004). However, as the particles are getting bigger, they decouple more efficiently from the surrounding gas. This leads to an increase in their relative collision velocities (Weidenschilling, 1977) and it is *a priori* not clear how large particles can grow by direct sticking. Many laboratory experiments have shown that millimeter-sized particles do not stick to each other if they collide at a velocity which is expected to occur under the conditions in a PPD (see review by Blum and Wurm (2008) and recent experiments by Beitz et al. (2011)). Indeed, the sticking velocities for those dust-aggregate sizes are so small that they are not yet known and need to be studied, and that is the goal of this paper.

1.1. The current collision model

Our current knowledge on the outcome of dust-aggregate collisions has been largely shaped by the collision model of Güttler et al. (2010). Based on available results from laboratory experiments, Güttler et al. quantified the outcome of a collision between two dust aggregates in terms of sticking, bouncing, and fragmentation. Moreover, their model predicts which of these outcomes actually occurs for a given set of collision parameters (dust-aggregate masses, dust-aggregate porosities, collision velocity) over a wide range of dust-aggregate masses and collision velocities. According to this model, the sticking velocity for millimeter-sized, porous dust aggregates (i.e. a mass of 0.1 mg) is as small as 10^{-3} m s^{-1}, which is slower than the expected collision velocities for these dust aggregates in a PPD (Weidenschilling and Cuzzi, 1993). The model of Güttler et al. was implemented into a local growth simulation (Zsom et al., 2010), and the result was that the growth in a minimum mass solar nebula stalls at masses of approximately 1 mg. Instead of further sticking to each other, the dust aggregates rebound and are compacted as observed in the experiments of Weidling et al. (2009). The picture changed when Zsom et al. (2011) included

* Corresponding author.
E-mail address: r.weidling@tu-braunschweig.de (R. Weidling).

0019-1035/$ - see front matter © 2011 Elsevier Inc. All rights reserved.
doi:10.1016/j.icarus.2011.10.002

the vertical dimension of the disk and sedimentation of the dust aggregates, because particles with different growth timescales get turbulently mixed and the size distribution becomes wider all over the disk.

Those results are expected to be very sensitive to the exact sticking threshold velocity. In the model by Güttler et al. this velocity is merely based on theoretical assumptions as there had been no experiments for millimeter-sized dust aggregates at the relevant velocities at that time. Therefore, it is most desirable to directly measure the threshold velocity for small, porous dust aggregates and to understand the physical processes involved. An implicit assumption of the Güttler et al. model is that the dust aggregates are homogeneous (but porous) spheres. This means that the model is not necessarily useable for fractal dust aggregates. An exact value for the fractal dimension of dust aggregates in this evolutionary phase remains highly speculative at this point (Ormel et al., 2007; Suyama et al., 2008; Okuzumi et al., 2009), but it is likely that dust aggregates crossing the threshold from sticking to bouncing for the first time possess a fractal dimension less than three. A measurement of the sticking threshold for fractal dust aggregates of the same size would be an ambitious next step but is not within the scope of this paper.

An additional challenge in this context are the differing existing definitions for fractal dust aggregates, especially for the radius and the volume. Jones (2011) recently presented a model parameterizing fractal and porous particles made up of finite-sized constituents. He describes such particles by means of an inflation and a dimensionality, which are derived from unambiguous properties of the particles, like the largest spatial extent of the particle or the volume the solid matter occupies. An advantage of this model is that particles do not have to be fractal in the strict mathematical sense to be described with these parameters.

To complement the picture on collisional grain growth in protoplanetary disks, we would like to mention that other effects are considered to play a role but are so far only sparsely studied. These involve magnetic fields and magnetized dust aggregates (Nübold and Glassmeier, 2000; Dominik and Nübold, 2002) as well as electrostatic effects to enhance the cross-sectional area and the sticking efficiency (Ivlev et al., 2002) and leading to reaccretion of bouncing dust grains (Blum, 2004). Additionally, gas effects might lead to the reaccretion of small fragments after a fragmenting collision (Wurm et al., 2001a,b). Another effect that increases the complexity is the rotation of the dust aggregates. This does not only lead to a more complicated treatment of the velocity (translational and rotational) in each individual collision with a possible influence on the sticking efficiency, but may also change the resulting shape of dust aggregates in the first growth phase (Paszun and Dominik, 2006).

1.2. Concept and background of our experiment

In order to investigate the transition from sticking to bouncing collisions for mm-sized porous dust aggregates, the particles have to collide with velocities of millimeters per second. With currently available techniques, these velocities are not feasible under standard laboratory conditions, whereas they can be achieved in microgravity experiments. Previous experiments by Heißelmann et al. (2010) describe a method to achieve very low collision velocities with solid particles: they injected an ensemble of 1 cm diameter glass beads from two opposing sides into a flat box under microgravity conditions. In this granular-gas experiment, each inelastic collision between two particles resulted in the dissipation of energy and, thus, in a lowering of the kinetic energy and velocity. Each additional collision slowed down the particles further, lowering the average collision velocity over time.

For dust particles, the coefficient of restitution – the ratio of the relative velocity of two colliding particles after and before a collision – is around $\varepsilon \simeq 0.2$ (Blum and Münch, 1993; Heißelmann et al., 2007). Compared to the average coefficient of restitution of the glass beads of 0.64 (Heißelmann et al., 2010) this means that an ensemble of dust particles is slowed down even more efficiently, provided that the average collision frequency is similar. This is evident from the mean velocity of an ideal system of equal-sized particles with velocity-independent ε:

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

(Heißelmann et al., 2010) generally referred to as Haff's law (Haff, 1983). Here, v_0 is the initial particle velocity at time $t = 0$, and n and σ are the number density and the collision cross section of the particles.

In order to be able to follow the trajectory of each particle throughout the whole experiment, Heißelmann et al. chose the dimensions of the chamber containing the glass beads to be 1.5 times as high as a single sphere diameter, preventing them from obscuring each other. A side effect of this quasi two-dimensional setup is that the particles collide with the walls very often. In the case of glass particles and glass walls this effect can be neglected (the coefficient of restitution in particle-wall collisions in their case was significantly higher than in particle-particle collisions). However, porous dust particles tend to stick to glass walls even at moderate velocities, which requires a larger test volume compared to the particle size. This leads to a slightly different implementation of the concept outlined by Heißelmann et al. and the details of our setup are described in the next section.

2. Experimental setup

Our experimental setups are described in detail in Sections 2.1, 2.2, and 2.3. To account for technical advances in the past and future, we will refer to the experiment by the acronym MEDEA (Microgravity Experiment on Dust Environments in Astrophysics) together with a number for the respective version of the experiment. In future efforts, the improvements of the experimental setup will help us to address some issues more accurately than we are able to do in this work.

In contrast to Heißelmann et al. we chose a cylindrical geometry for our test chambers (see Fig. 1). We use glass vacuum chambers with a diameter of 25 mm and a height of 50 mm. These can be agitated in a sinusoidal oscillation along the cylinder axis to excite the dust particles inside. In microgravity, the dust aggregates are observed with high-speed cameras in back-light illumination. According to Eq. (1), a high number density of dust particles is desirable, which however constrains the observability of the dust aggregates. To optimize collision time and observability, we chose an optical depth of approximately 0.3, resulting in number densities from $n = 5 \times 10^5$ to $5 \times 10^9\ \mathrm{m}^{-3}$ depending on the particle size. For 0.75 mm diameter dust aggregates this leads to a collision time $\tau = (n\sigma v)^{-1} \approx 0.16$ s, with $v = 0.1\ \mathrm{m\,s}^{-1}$ being a typical relative velocity at the beginning of the experiment.

2.1. First setup (MEDEA-I)

The first experimental setup, which we will refer to as MEDEA-I, was used in an experiment campaign at the Bremen drop tower in June 2010. Utilizing the catapult, we obtained a microgravity time of nearly 9.5 s in each of our 10 flights. We used four identical setups, i.e. four test chambers and four cameras, in each flight, resulting in 40 experiments to extensively test and develop the setup