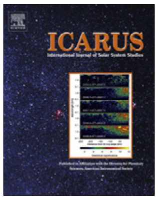
Icarus 218 (2012) 701–706

Contents lists available at SciVerse ScienceDirect

Icarus

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



Free collisions in a microgravity many-particle experiment – II: The collision dynamics of dust-coated chondrules

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

[a] Institut für Geophysik und extraterrestrische Physik, Technische Universität 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 9 December 2011

Keywords:
Experimental techniques
Planetary formation
Solar nebula
Planetesimals
Meteorites

ABSTRACT

The formation of planetesimals in the early Solar System is hardly understood, and in particular the growth of dust aggregates above millimeter sizes has recently turned out to be a difficult task in our understanding (Zsom, A., Ormel, C.W., Güttler, C., Blum, J., Dullemond, C.P. [2010]. Astron. Astrophys., 513, A57). Laboratory experiments have shown that dust aggregates of these sizes stick to one another only at unreasonably low velocities. However, in the protoplanetary disk, millimeter-sized particles are known to have been ubiquitous. One can find relics of them in the form of solid chondrules as the main constituent of chondrites. Most of these chondrules were found to feature a fine-grained rim, which is hypothesized to have formed from accreting dust grains in the solar nebula. To study the influence of these dust-coated chondrules on the formation of chondrites and possibly planetesimals, we conducted collision experiments between millimeter-sized, dust-coated chondrule analogs at velocities of a few cm s^{-1}. For 2 and 3 mm diameter chondrule analogs covered by dusty rims of a volume filling factor of 0.18 and 0.35–0.58, we found sticking velocities of a few cm s^{-1}. This velocity is higher than the sticking velocity of dust aggregates of the same size. We therefore conclude that chondrules may be an important step towards a deeper understanding of the collisional growth of larger bodies. Moreover, we analyzed the collision behavior in an ensemble of dust aggregates and non-coated chondrule analogs. While neither the dust aggregates nor the solid chondrule analogs show sticking in collisions among their species, we found an enhanced sicking efficiency in collisions between the two constituents, which leads us to the conjecture that chondrules might act as "catalyzers" for the growth of larger bodies in the young Solar System.

1. Introduction

Chondrules are millimeter-sized solid particles, which are found in large amounts in meteorites. Petrographic studies of these chondrules revealed that their formation dates back to an early time interval in the solar nebula, only 2.5 ± 1.2 Myrs after the first condensates and the calcium–aluminum-rich-inclusions formed (Amelin et al., 2002). As chondrules make up between 20% and 80% of their parent bodies' volume (Hewins et al., 2005), their mere ubiquity indicates a tight connection to the formation of planetesimals. Metzler et al. (1992) analyzed 14 carbonaceous chondrites and determined that all chondrules are surrounded by a dusty layer, referred to as accretionary rims, which are hypothesized to be a record of the accretion of dust grains in the solar nebula (Metzler et al., 1992; Morfill et al., 1998; Bland et al., 2011). These dusty rims will likely have an influence on the collision behavior of the chondrules and, thus, on the formation of planetesimals (Ormel et al., 2008). Especially since Zsom et al. (2010) discovered a bouncing barrier for millimeter-sized dust aggregates, which prevents any further mass increase of the dust aggregates, the growth mechanisms beyond this size need further investigation. For the chondrules we firmly know that they existed before the planetesimals were formed. On the account that the formation process of the chondrules is still under discussion, it could also be likely that not all dust aggregates were consumed to form igneous particles so that the remaining dust aggregates and the freshly-formed chondrules could have co-existed.

With this in mind, we experimentally tested the influence of porous dust rims around artificial chondrules and the co-existence of chondrule analogs and dust aggregates on their collision behavior in free particle–particle collisions. To achieve this, we first developed two different techniques to cover chondrule analogs with dusty layers, simulating their formation in the solar nebula (Sections 2.1 and 3.1). In a second step, the dust-coated chondrule analogs were used in a multiple collision experiment, in which we observed low-velocity collisions (typically at a few cm s^{-1}) between dust-coated particles of 2 and 3 mm in diameter (Sections 2.2 and 3.2). Additionally, we performed a collision experiment between dust aggregates and chondrule analogs with a diameter of 2 mm each, to test the influence of the presence of solid particles on the formation of larger bodies.

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* Corresponding author.
E-mail address: e.beitz@tu-bs.de (E. Beitz).

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doi:10.1016/j.icarus.2011.11.036

2. Experimental setup

2.1. Coating experiments

We used two different experimental methods to prepare dust rims around chondrule analogs, resulting in simulated accretionary rims of different porosities and morphologies. As chondrule analogs, we used glass beads of 2 and 3 mm diameter, respectively.

The first setup is designed to create highly porous dust rims in collisions between a chondrule analog and individual micrometer-sized dust grains at velocities below the sticking threshold. This experiment is intended to simulate free-floating chondrules in the solar nebula, which gently collide with single dust grains, which then stick to their surfaces (Morfill et al., 1998). To reproduce such a scenario, we levitated a glass bead (the chondrule analog) in a vertical upward gas stream within a hollow funnel. The gas flow from below the chondrule analog is adjustable so that we can levitate glass spheres between 1 and 4 mm in diameter without touching the funnel wall. Using an aerosol generator, we introduced single micrometer-sized dust grains into the gas flow, which stick to the chondrule's surface. A typical dust-coated chondrule analog formed with this method is shown in the inset of Fig. 2a and the properties of the dust rims are presented in Section 3.1. For this method, we determined the collision velocity between the levitated glass bead and the dust grains, assuming perfect coupling of the dust particles to the gas flow, to be $v_{\mathrm{coll}} \leqslant 0.8\ \mathrm{m\ s^{-1}}$. This velocity determination is based on the measurement of the gap width between the levitated glass sphere and the funnel wall with a camera mounted such that the experiment could be observed from the top. Additionally, the gas flux through the funnel was measured so that the equation of continuity yields the gas velocity in the gap. This value overestimates the gas velocity and denotes the upper limit of the collision velocity of the individual dust particles with the surface, because (i) the dust particles never completely couple to the gas flow and (ii) the gas velocity at the surface of the glass bead possesses only a tangential velocity component whereas the collision velocity between dust and glass bead is dominated by the normal component. Nevertheless, the estimated upper limit is still sufficiently below the sticking velocity of $1.1\ \mathrm{m\ s^{-1}}$ determined by Blum et al. (2006) to guarantee a high sticking probability. Moreover, for these low velocities, we do not expect any severe restructuring (Blum and Wurm, 2000; Blum et al., 2006) or even erosion (Schräpler and Blum, 2011) of the dusty surface, and this is consistent with the low volume filling factor of $\phi = 0.18 \pm 0.05$ measured for the accreted dust rims (see Section 3.1). For the determination of the volume filling factor, we used a rotation table and a high-resolution camera (for the volume determination, resolution 4 μm/pixel) and a precision balance (for the mass determination) with an accuracy of 0.1 mg, details are described by Weidling et al. (in press, hereafter Paper I). The coating is rather homogeneous over the surface of the glass bead, but due to the handling processes using tweezers and due to the storage, a small fraction of the dust-coated surface exhibits depressions or abrasions (see inset of Fig. 2a). We consider the influence of these imperfections as minor.

The second method simulates a multiple-collision scenario in which mass is transferred to the chondrule surfaces in many low-velocity collisions with porous dust agglomerates. To assemble these rims, we randomly shake a container of dust with a glass bead inside for a defined time (e.g., 60 s). With this method, the glass beads accrete a denser rim in comparison to the first method described above. We estimated the volume filling factor to be $0.35 \leqslant \phi \leqslant 0.58$ (see Section 3.1). The inset in Fig. 2b shows such a chondrule analog, which has a more irregular rim than the one shown in Fig. 2a.

For both coating scenarios, we used spherical monodisperse SiO_2 dust grains with a grain diameter of 1.5 μm (properties compiled by Blum et al. (2006)). This dust has been used for many dust-aggregate collision experiments (Blum and Wurm, 2008; Güttler et al., 2010), and also its material and aggregate properties are well known (Heim et al., 1999; Blum et al., 2006).

For the experiment in which we observed collisions between un-coated glass beads and dust aggregates, the dust aggregates consisted of polydisperse SiO_2 dust grains and had a diameter of about 2 mm. These particles are the same as described in Paper I, with a volume filling factor of $\phi = 0.35 \pm 0.05$.

2.2. Multiple collision experiments

The main objective of this study is to investigate low-velocity collisions between the protoplanetary dust analogs (dust aggregates, pure chondrules, dust-coated chondrules) and to determine their sticking threshold velocity. To achieve the required low velocities, the experiments were performed under microgravity conditions in the Bremen drop tower, and the setup used here is the many-particle collision experiment MEDEA-II as described in detail in Paper I. The setup consists of a glass tube under vacuum (residual gas pressure ~0.1 Pa) with a diameter of 25 mm, in which the particles can collide freely. The experiment chamber is observed by a high-speed camera operated at 500 frames per second, using a beam splitter optics with a viewing angle of 30° to obtain the three-dimensional trajectory information. In this paper we use only one projection for the determination of the collision velocity. However, Paper I showed that the major component to the collision velocity is in the direction parallel to the shaking direction and that a two dimensional treatment underestimates the collision velocity by only 13%. In the case of hypothetical sticking, we used the second camera projection to ensure that sticking really occurred. Within the experimental campaign in November 2010, we performed four experiments with dust-coated chondrule analogs (using 2 and 3 mm diameter glass beads and the two rim porosities described above, we conducted one experiment for each combination), and one experiment with a mixture of solid glass beads and dust aggregates. During approx. 9 s of microgravity time, the vacuum tube was gently shaken with an eccentric wheel (1 mm amplitude, 4 or 16 Hz maximum shaking frequency) to separate the chondrule analogs and dust aggregates at the beginning of the experiment and to prevent their sticking to the walls at a later stage. In each of the four experiments with dust-coated chondrule analogs described below, 60–140 particles were carefully prepared and stored at the bottom of the test chamber in a conical pile. In the experiments with the fluffier rims, the vacuum tube was continuously excited by a fast shaker (16 Hz), in the runs with the denser rims, the shaker was running at a lower frequency (4 Hz), which was even slowed down (approx. 2 Hz) after 3 s with a motor control. By this, we intended to achieve even lower collision velocities, but this had the side effect that the particles were clumping rapidly and no further individual collisions could be observed. In the fifth experiment, we used 40 un-coated glass beads and 95 dust aggregates with a diameter of 2 mm each. These are the same dust aggregates which were used in the experiments of Paper I. The dust aggregates possessed a volume filling factor of $\phi = 0.35 \pm 0.05$. The shaker frequency in this experiment was 16 Hz for the first 2 s and then reduced to 8 Hz for the remaining 7 s.

3. Results

3.1. Rim properties

The two different coating mechanisms described in Section 2.1 result in two different types of chondrule rims. The rims formed by free-floating chondrules in the funnel could well be characterized