

# Microgravity experiments on the collisional behavior of saturnian ring particles

Daniel Heißelmann<sup>a,\*</sup>, Jürgen Blum<sup>a</sup>, Helen J. Fraser<sup>b</sup>, Kristin Wolling<sup>a</sup>

<sup>a</sup> Institut für Geophysik und extraterrestrische Physik, Technische Universität Braunschweig, Mendelssohnstraße 3, 38106 Braunschweig, Germany

<sup>b</sup> Department of Physics, University of Strathclyde, SUPA (Scottish Universities Physics Alliance), John Anderson Building, 107 Rottenrow East, Glasgow G4 0NG, United Kingdom

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## ABSTRACT

In this paper we present results of two novel experimental methods to investigate the collisional behavior of individual macroscopic icy bodies. The experiments reported here were conducted in the microgravity environments of parabolic flights and the Bremen drop tower facility. Using a cryogenic parabolic-flight setup, we were able to capture 41 near-central collisions of 1.5-cm-sized ice spheres at relative velocities between 6 and 22 cm s<sup>-1</sup>. The analysis of the image sequences provides a uniform distribution of coefficients of restitution with a mean value of  $\bar{\varepsilon} = 0.45$  and values ranging from  $\varepsilon = 0.06$  to 0.84. Additionally, we designed a prototype drop-tower experiment for collisions within an ensemble of up to one hundred cm-sized projectiles and performed the first experiments with solid glass beads. We were able to statistically analyze the development of the kinetic energy of the entire system, which can be well explained by assuming a granular 'fluid' following Haff's law with a constant coefficient of restitution of  $\varepsilon = 0.64$ . We could also show that the setup is suitable for studying collisions at velocities of <5 mm s<sup>-1</sup> appropriate for collisions between particles in Saturn's dense main rings.

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## 1. Introduction

Saturn's rings are one of the most tremendous astronomical objects in our Solar System, and have been studied for centuries by ground-based astronomy (G. Galilei, J. D. Cassini). More recently, deep-space missions (e.g. *Voyager* and *Cassini*) have allowed for in-depth investigations of these structures. Today it is clear that the dense main rings (A, B and C ring and Cassini Division) consist of myriads of particles orbiting Saturn in Keplerian orbits creating a disk only a few meters thick (Tiscareno et al., 2007; Hedman et al., 2007; Porco et al., 2008). Spectroscopic observations (Poulet et al., 2003; Nicholson et al., 2008) and radio occultation data (Tyler et al., 1981; Marouf et al., 1983; Zebker et al., 1985) have confirmed that the rings consist predominantly of bodies of almost pure water ice, with sizes between 1 cm and 10 m. Many of the observed ring features are caused by interactions with nearby moons and moonlets which gravitationally perturb their trajectories and thus increase their orbital eccentricity and the ring thickness. Counteracting this, frequent inelastic collisions at very low relative velocities ( $v \lesssim 0.5$  cm s<sup>-1</sup>, see review by Esposito (2002)) are means to dissipate kinetic energy and thereby re-circularize the orbits and confine the height of the ring plane.

Several theoretical and numerical studies have been carried out to investigate the formation of structures inside the dense rings,

the evolution of ring-particle orbits over time and the expected outcome of typical collisions between ring particles. Kinetic theories were first developed by Goldreich and Tremaine (1978) and Hameen-Anttila (1978), based on earlier work by Trulsén (1971, 1972). These theories, which were applicable to thin granular gases of a single species (i.e. one particle size), were extended to dense granular disks (Borderies et al., 1985; Araki and Tremaine, 1986; Araki, 1991), and subsequently explored with N-body simulations (e.g. Wisdom et al., 1988; Salo, 1991a,b) that also included the particle size distribution described by Zebker et al. (1985). In addition, visco-elastic collision models, developed by Spahn et al. (1995) and Brilliantov et al. (1996), have been extended to also treat fragmentation and coagulation (Spahn et al., 2004; Albers and Spahn, 2006). The models of Schmidt et al. (2001) and Salo et al. (2001) show that the amount of energy dissipated through collisions determines the stability of homogeneous dense rings, and thus is a crucial parameter in understanding the formation of structures, instabilities and wakes as observed in Saturn's rings (Colwell et al., 2006; Colwell et al., 2007; Hedman et al., 2007; Thomson et al., 2007).

In most N-body simulations and kinetic theories, the inelastic collisional behavior is described by a single parameter, the coefficient of restitution  $\varepsilon$ , which is the ratio of the relative velocities  $v'$  after the encounter to the relative velocities  $v$  before the encounter, and is a measure of the dissipation of the kinetic energy. Although ice-particle collisions play a vital role in determining the stability and evolution of Saturn's rings, as well as in the formation of icy planetesimals in protoplanetary disks, their collision

\* Corresponding author. Fax: +49 531 391 5220.

E-mail addresses: [d.heisselmann@tu-bs.de](mailto:d.heisselmann@tu-bs.de) (D. Heißelmann), [j.blum@tu-bs.de](mailto:j.blum@tu-bs.de) (J. Blum), [h.fraser@phys.strath.ac.uk](mailto:h.fraser@phys.strath.ac.uk) (H.J. Fraser), [k.wolling@tu-bs.de](mailto:k.wolling@tu-bs.de) (K. Wolling).

properties have hardly been investigated in the low velocity regime. Previous experiments carried out by Bridges et al. (1984) and Hatzes et al. (1988), used a disk pendulum to study central impacts of large ice bodies onto a flat solid ice target, and showed a decrease in the coefficient of restitution with decreasing impact velocity and increasing amount of surface frost. The experiments were extended to include grazing collisions of polished ice spheres (Supulver et al., 1995). Higa et al. (1996, 1998) conducted impact experiments of different-sized ice spheres ( $r = 0.14\text{--}3.6\text{ cm}$ ) into a larger ice target. They found that the coefficient of restitution decreases with increasing particle size and is independent of temperature.

A major limitation of all these experimental studies (Bridges et al., 1984; Hatzes et al., 1988; Higa et al., 1996, 1998) is that they only treat impacts into a large body of infinite mass and infinitesimal surface curvature. In the case of the pendulum experiments an additional problem is that the mass and moment of inertia of the ice sphere are not realistic as they reflect those of the sample-pendulum-system instead of that of the individual projectile. However, the results obtained by Bridges et al. (1984) are commonly used in numerical simulations of Saturn's rings.

In this work we present two novel experimental methods for investigating collisions of saturnian ring particles. In Section 2 the two experimental setups for collisions of individual ice particles and ensembles of particles are described. The results of our microgravity experiment campaigns are presented in Section 3, and their application to Saturn's dense rings is given in Section 4.

## 2. Experimental setup

For our microgravity studies we used two different experimental approaches. The parabolic-flight setup was designed to study collisions of pairs of individual ice projectiles, whereas the Bremen drop tower facility experiment is a prototype, built to study a large number of low-velocity collisions within an ensemble of particles.

Microgravity is required to be able to investigate low-velocity pair-collisions of free particles with an arbitrary impact parameter (i.e. from central to grazing collisions), because it is the only way to access all the translational and rotational degrees of freedom. Parabolic flights offer typically 22 s of weightlessness per parabola with a residual acceleration of a few times  $0.01g_0$ , where  $g_0$  is Earth's gravitational acceleration. Drop-tower experiments achieve residual accelerations of better than  $10^{-5}g_0$  for up to 9 s.

### 2.1. Parabolic-flight experiment

Measurements were conducted on the German Space Agency's (DLR) 12th Parabolic Flight Campaign, using a setup consisting of a cryogenic cooled experiment body, placed inside a high-vacuum chamber. The experimental apparatus is composed of a massive copper block which acts as a thermal reservoir, with a rotating sample repository covered by a copper shield, which plays both a protective and cryo-cooling role. The entire system is initially cooled to roughly 77 K with liquid nitrogen ( $N_2$ ) spiraling through an attached pipe system. Up to 34 pairs of cm-sized ice particles can be stored in the sample repository, which allows us to collide approximately one pair per parabola. To accelerate the ice particles into the collision volume, two diametrically opposed pistons are used, driven by two synchronized DC motors, which accelerate the particles to maximum velocities between 3 and  $17\text{ cm s}^{-1}$ . These are positioned outside the cryo-vacuum chamber, and enter the vacuum by differentially pumped feedthroughs. Since the projectiles are driven towards each other from exactly opposite directions, the resulting binary collisions are predominantly centralized, with normalized impact parameters,  $b/R$ , close to zero, where  $b$  is

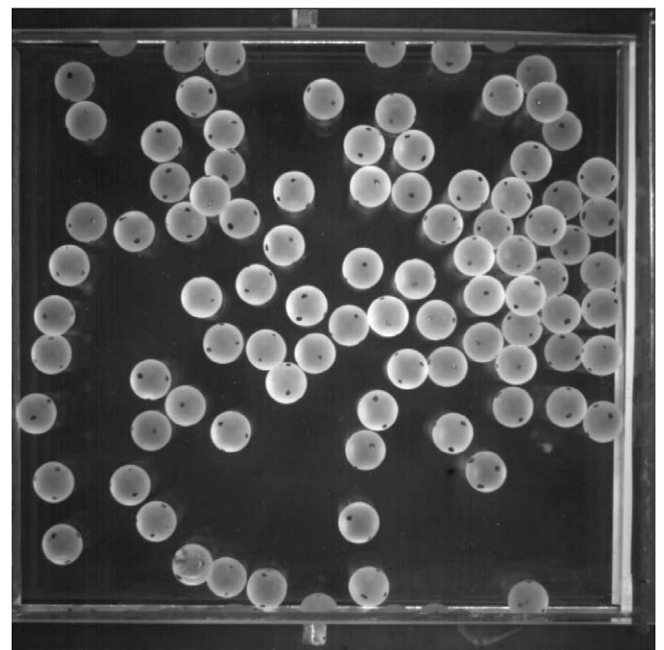
the center-of-mass distance of the two projectiles perpendicular to the velocity vector, and  $R$  is sum of the particles' radii. The collisions are recorded with a high-speed, high-resolution digital recording system, operating at 107 frames per second (fps) and equipped with beam-splitter optics to provide full three-dimensional collision information (i.e. impact parameter and relative velocity). For a more detailed technical description please refer to Salter et al. (2009).

Forty-one image sequences of colliding ice spheres (15 mm diameter) were recorded during DLR's 12th Parabolic Flight Campaign in April 2008. The samples were produced by freezing purified water inside silicone molds in a regular kitchen freezer, to produce 15 mm-sized, hexagonal-ice spheres. After removing the molds from the freezer, the spheres were extracted and stored inside a bath of liquid  $N_2$  from where they were individually loaded into the sample repository, which had been pre-cooled, and cooled further to temperatures of  $\sim 80\text{ K}$ . This procedure is required to minimize the amount of frost on the samples' surfaces. Although the maximum exposure time of the samples to the humid air was less than 1 min, some experiments show tiny amounts of surface material (which might be frost) chipped off during the collisions.

Since liquid  $N_2$  is prohibited on board the parabolic-flight aircraft, the cooling procedure had to be stopped before take-off. Consequently, the thermal block warmed slightly prior to take-off, and subsequently during flight, resulting in sample temperatures ranging from 130 to 180 K.

### 2.2. Drop-tower experiment

A quasi-two-dimensional rectangular glass box of  $150 \times 150 \times 15\text{ mm}^3$  volume (see Fig. 1) was constructed to investigate a large number of collisions within an ensemble of  $\sim 100$  (cm-sized) particles. The test-chamber's walls are made of 2 cm thick glass to ensure highly elastic collisions between the sample particles and the walls. Two sets of up to 50 projectiles, stored opposite each other, were accelerated into the test chamber with an initial



**Fig. 1.** Single image of an ensemble of cm-sized glass spheres colliding in microgravity. The black dots on the particles are marks for later use in the determination of particle rotation (see additional online material).

velocity of  $\sim 10 \text{ cm s}^{-1}$  by two motor-driven glass bars that afterwards seal these entry holes (Fig. 1). During the 9 s of microgravity,<sup>1</sup> the particle positions were recorded by a high-speed, high-resolution camera operating at 115 fps, and two overview cameras (25 fps) positioned at an angle of  $16.25^\circ$  relative to the chamber, to enable three-dimensional trajectory reconstruction.

Here we focus on the results of one out of seven microgravity experiments conducted at the Bremen drop tower in April 2008. This was a prototype experiment for future investigations that will be equipped with cryogenic facilities and therefore use ice particles. However in this case, the experiment was performed with 92 spherical glass samples of 10 mm diameter, with a slightly roughened surface. At the beginning of the microgravity period, two sets of 32 particles were injected into the test chamber where 28 samples were at rest. The experiment chamber was not evacuated, but the influence of the air drag acting on a sample particle does not significantly affect its velocity. A smooth glass sphere (10 mm diameter) has a Reynolds number  $Re \approx 1.6$  at a velocity of  $v = 4 \text{ mm s}^{-1}$  and  $Re \approx 62$  at a velocity of  $v = 10 \text{ cm s}^{-1}$ . From this the relative velocity loss  $\Delta v/v$  due to air drag between two consecutive collisions can be estimated to be less than a few times  $10^{-3}$ .

Standard methods of image processing and particle tracking were used to obtain the particles' positions from the recorded image sequence. A statistical analysis of all particles' velocities as a function of time was performed, which means that – although generally possible – we did not treat individual collisions but concentrated on the velocity development of the entire ensemble. In future experiments, the individual collisions, their impact parameters and the excitation of rotational motion will be investigated. The results of our analyses can be found in Section 3.2.

### 3. Results

#### 3.1. Parabolic-flight experiment

The binary collision experiments performed during DLR's 12th Parabolic Flight Campaign occurred in free space and so were truly three-dimensional events. Thus, data from two projections of each event captured using beam-splitter optics (at an angular separation of  $48.8^\circ$ ) were used to determine the particle motion (see Fig. 2). The two sets of two-dimensional coordinates were combined with a transformation algorithm to produce the sample coordinates in three dimensions, and the trajectories were determined by linear fits to the data. From this, the relative velocities before and after the collision,  $v$  and  $v'$  respectively, and the normalized impact parameter,  $b/R$ , were calculated. Additionally, the velocity components normal and tangential to the colliding surfaces ( $v_\perp$  and  $v_\parallel$ , respectively) could be extracted.

From Fig. 3 it is clear that the impact parameters are restricted to near-central collisions (due to the limitations of our experimental setup), ranging from  $b/R = 0$  to  $0.5$  with a mean value  $\bar{b}/R = 0.16$ . However, simple geometrical considerations show that in reality glancing collisions are the most frequent ones. Thus the captured collisions with impact parameters smaller than  $b/R = 0.5$  cover only a fraction of  $P$  (i.p.  $<0.5$ )  $= (b/R)^2 = 0.25$  of the statistically occurring impacts in Saturn's rings. From the observed impact parameters and coefficients of restitution no evidence for a correlation between these parameters could be found by linear correlation analysis, in which we computed the linear correlation coefficient:

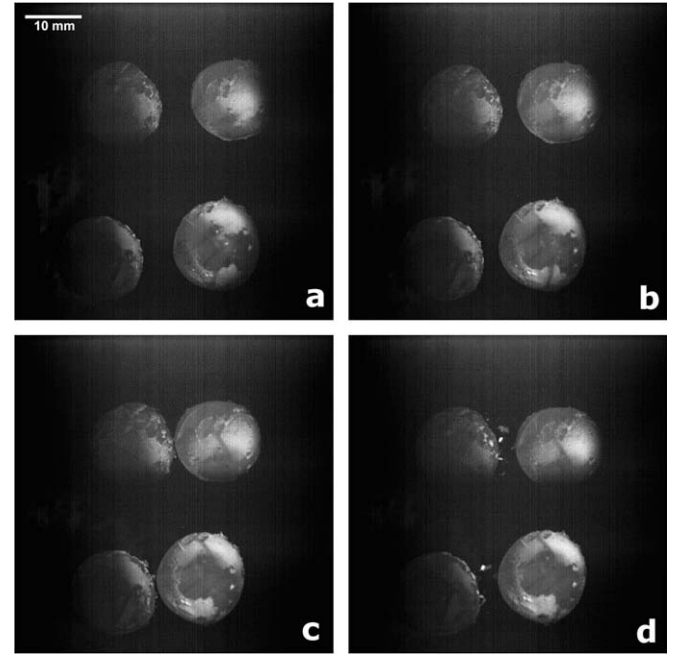


Fig. 2. Image sequence of two 15-mm-sized ice spheres colliding at a relative velocity of  $14 \text{ cm s}^{-1}$ . The temporal separation between two consecutive frames is  $\frac{4}{107} \text{ s}$ . The images were captured using a beam-splitter optics. Therefore, each image frame contains two views of the set of particles, which are separated by an angle of  $48.8^\circ$ .

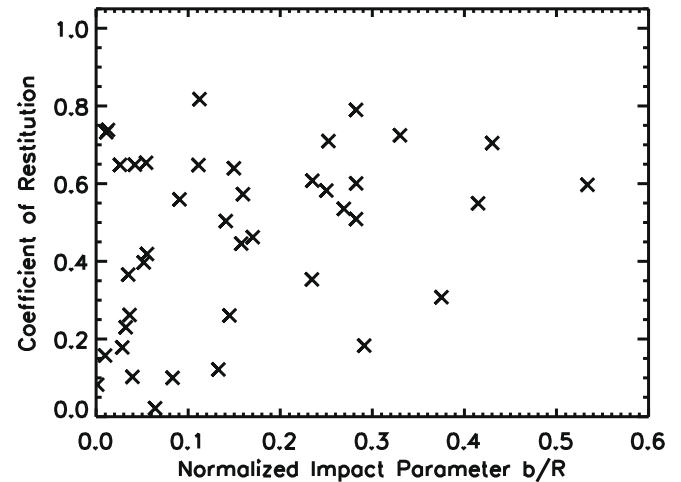
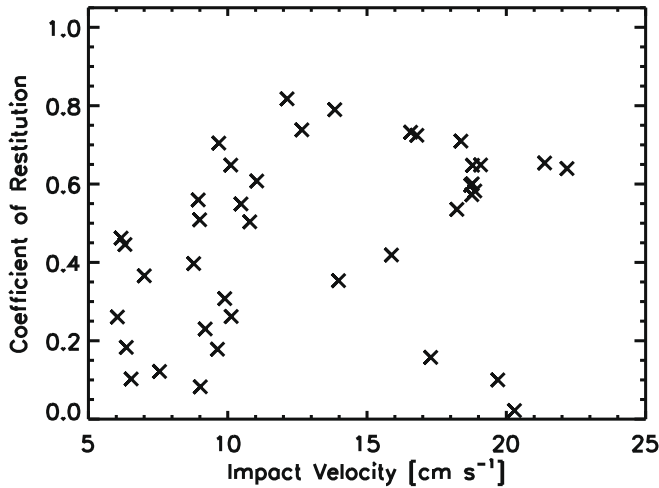


Fig. 3. Obtained coefficients of restitution for ice-particle collisions at near-central impact parameters in the range  $b/R = 0$ – $0.5$ . There is no evidence of a correlation between the two variables.

$$r_{b/R} = \frac{\sum_{i=0}^n (\varepsilon_i - \bar{\varepsilon}) \left( \frac{b_i}{R_i} - \bar{\frac{b}{R}} \right)}{\sqrt{\sum_{i=0}^n (\varepsilon_i - \bar{\varepsilon})^2} \cdot \sqrt{\sum_{i=0}^n \left( \frac{b_i}{R_i} - \bar{\frac{b}{R}} \right)^2}}, \quad (1)$$

where  $r_{b/R}^2 = 0.10$  gives the fraction of the data which can be explained by a linear dependence. Based on a similar analysis of the coefficient of restitution  $\varepsilon$  and the relative impact velocity  $v$  ( $r_v^2 = 0.11$ ; see Fig. 4) a correlation of those can also be ruled out. In a detailed analysis of the coefficient of restitution in normal ( $\varepsilon_\perp$ ) and tangential direction ( $\varepsilon_\parallel$ ) no evidence for a correlation of these values with the impact parameter or the impact velocity could be found. Elaborate investigation showed that also a depen-

<sup>1</sup> The use of the Bremen drop tower's catapult facility almost doubled the duration of microgravity compared to a regular drop without using the catapult.



**Fig. 4.** Obtained coefficients of restitution for ice-particle collisions in the velocity range  $v = 6\text{--}22\text{ cm s}^{-1}$ . A linear correlation analysis shows no evidence for a correlation between these variables.

dence of the coefficient of restitution on a combination of the collision velocity and the impact parameter could be ruled out.

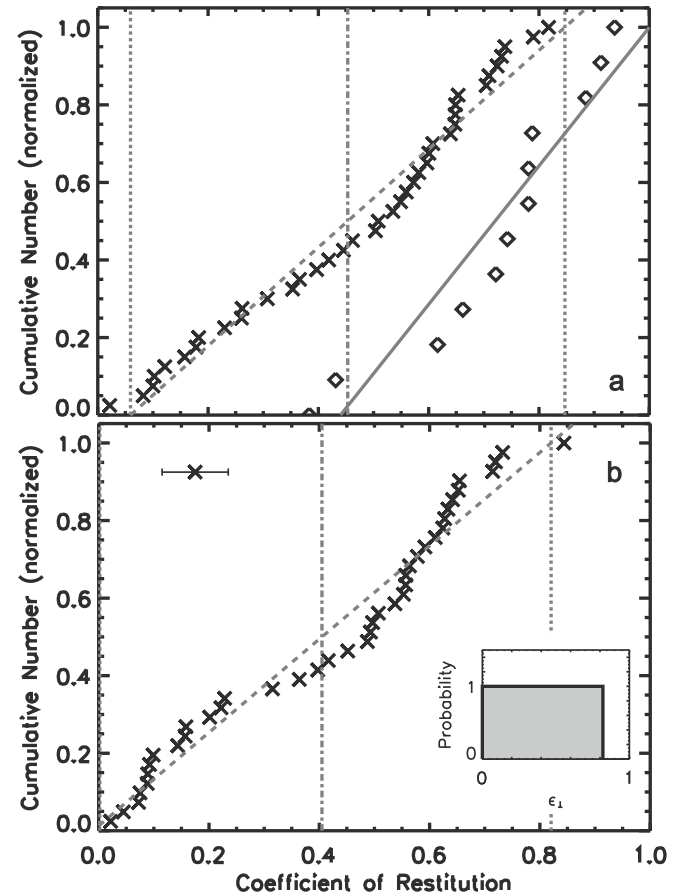
Hence, we can treat the coefficient of restitution data in a statistical way. One way to do this, is to plot the cumulative number of collisions with a coefficient of restitution  $\leq \varepsilon$  (Fig. 5a). It turns out that this can be fitted by a uniform distribution (see dashed curve in Fig. 5a). The fit provides a mean coefficient of restitution of  $\bar{\varepsilon} = 0.45$  and an overall range of  $\varepsilon = 0.06\text{--}0.84$  (dotted lines in Fig. 5a).

The obtained normal coefficient of restitution  $\varepsilon_{\perp}$  was treated in a similar way. Fig. 5b shows that values of  $\varepsilon_{\perp}$  fall in the interval  $0 \dots 0.82$  (dashed lines). The analysis of our dataset yields a mean value  $\bar{\varepsilon}_{\perp} = 0.41$  with an error of the mean  $\sigma_{\bar{\varepsilon}_{\perp}} = 0.04$  and individual measurement errors of  $\Delta\varepsilon_{\perp} = 0.06$ . The standard deviation of the individual measurements from the mean value was calculated to  $\sigma_{\varepsilon_{\perp}} = 0.24$  indicating a significant scatter of the values for  $\varepsilon_{\perp}$  around  $\bar{\varepsilon}_{\perp}$  which is not caused by the measurement uncertainties. We therefore recommend to include a flat statistical distribution of coefficients of restitution (see insert in Fig. 5b) rather than a single value to the models investigating Saturn's rings. However, it is likely that the wide range of coefficients of restitution observed in our parabolic-flight experiments reflects the anisotropic nature of the ice samples' surface properties, especially the surface roughness or previously slightly melted areas altering the collisional properties.

For the analysis of the tangential component  $\varepsilon_{\parallel}$  only experiments with tangential velocities  $v_{\parallel} \geq 5\text{ mm s}^{-1}$  (36 out of 41 experiments) were taken into account to avoid  $\varepsilon_{\parallel} = v'_{\parallel}/v_{\parallel}$  approaching unrealistically large values when the denominator  $v_{\parallel}$  approaches zero. The mean value of the tangential coefficient of restitution was measured to be  $\bar{\varepsilon}_{\parallel} = 1.08$  with an error of  $\sigma_{\bar{\varepsilon}_{\parallel}} = 0.19$  and individual standard deviation of  $\sigma_{\varepsilon_{\parallel}} = 1.11$ , which is in fair agreement with the value found by Supulver et al. (1995). The large individual measurement errors of  $\Delta\varepsilon_{\parallel} = 0.38$  (due to the small absolute values of  $v_{\perp}$ ) do not allow any secure interpretation, however. Table 1 summarizes our experimental results for the normal and tangential coefficient of restitution of binary collisions between cm-sized ice spheres.

### 3.2. Drop-tower experiment

To yield the positions of all particles in all image frames, the images were convolved with an image of a single sphere as kernel. The probability maxima, which determine the particle positions, could then be detected automatically. The tracking of all particles



**Fig. 5.** (a) Normalized cumulative number of ice-particle collisions with coefficients of restitution  $\leq \varepsilon$  for all captured collisions in the parabolic-flight experiments (crosses). The distribution of  $\varepsilon$  can be fitted by a uniform distribution which is given by the dashed curve. The mean coefficient of restitution is at  $\bar{\varepsilon} = 0.45$  (denoted by the dash-dotted line) with an overall range of  $\varepsilon = 0.06\text{--}0.84$  (dotted lines). The diamonds represent the data obtained from binary collisions of glass beads in the laboratory mini drop tower. The coefficients of restitution span a range of  $\varepsilon \approx 0.35\text{--}0.95$  (solid curve). (b) Normalized cumulative number of collisions with normal coefficients of restitution  $\leq \varepsilon_{\perp}$  for all 41 captured experiments. The normal component has a mean value of  $\bar{\varepsilon}_{\perp} = 0.41 \pm 0.04$  with a standard deviation of individual measurements of 0.24. The measurement error of an individual measurement is 0.06 (indicated by the error bars). The insert shows a schematic distribution of coefficients of restitution that could be included into numerical simulations.

**Table 1**

Summary of the experimental results of the coefficient of restitution of low-velocity ice-particle collisions. The velocity range was  $v_{\perp} = 4 \dots 22\text{ cm s}^{-1}$  and  $v_{\parallel} = 0.5 \dots 8\text{ cm s}^{-1}$ , respectively.

$\varepsilon_{\perp}$		$\varepsilon_{\parallel}$					
$\bar{\varepsilon}_{\perp}$	$\sigma_{\bar{\varepsilon}_{\perp}}$	$\sigma_{\varepsilon_{\perp}}$	$\Delta\varepsilon_{\perp}$	$\bar{\varepsilon}_{\parallel}$	$\sigma_{\bar{\varepsilon}_{\parallel}}$	$\sigma_{\varepsilon_{\parallel}}$	$\Delta\varepsilon_{\parallel}$
0.41	0.04	0.24	0.06	1.08	0.19	1.11	0.38

$\bar{\varepsilon}_{\perp}, \bar{\varepsilon}_{\parallel}$ : mean normal/ tangential coefficient of restitution.

$\sigma_{\bar{\varepsilon}_{\perp}}, \sigma_{\bar{\varepsilon}_{\parallel}}$ : error of mean normal/tangential coefficient of restitution.

$\sigma_{\varepsilon_{\perp}}, \sigma_{\varepsilon_{\parallel}}$ : standard deviation of individual measurements of normal/tangential coefficient of restitution from mean value.

$\Delta\varepsilon_{\perp}, \Delta\varepsilon_{\parallel}$ : measurement uncertainty of individual measurement of normal/tangential coefficient of restitution.

over time allowed the calculation of the individual particle's mean velocity<sup>2</sup> between consecutive images. The resulting particle velocity

<sup>2</sup> The reader should note that although the term 'velocity' generally describes a vectorial quantity we use it for the absolute value of the velocity. In all cases treating the velocity as a vector this is clearly stated.



ties as a function of time show that the system equilibrates very quickly within the first 1.5 s. After this injection phase, we observed dissipation of kinetic energy through inelastic collisions and transformation to rotational motion which was visualized by black marks on the surface of the glass beads (see Fig. 1).

From the analysis of the particle velocities within the last 1.5 s of experiment time, we obtained a median particle velocity of  $3.5 \text{ mm s}^{-1}$  and determined that 50% of the particles are moving with velocities between 2 and  $5 \text{ mm s}^{-1}$  (see dashed and dotted lines in Fig. 6), which corresponds fairly well to the desired velocities for studying collisions in Saturn's dense rings (Esposito, 2002).

The decay of the mean particle velocity of the entire ensemble during the experiment duration is displayed in Fig. 7a. The individual measurements were logarithmically binned and the mean velocity was computed. The error bars denote the standard deviation of the velocity and experiment time measurements, respectively. Assuming a constant coefficient of restitution  $\varepsilon(v) = \text{const.}$ , the simple kinetic theory for granular fluids presented by Haff (1983) indicates that the temporal rms-velocity evolution can be described by the following function:

$$v(t) = \frac{1}{\frac{1}{v_0} + (1 - \varepsilon) \cdot n \cdot \sigma \cdot t}, \quad (2)$$

where  $v_0$  is the initial injection velocity of the ensemble,  $n$  is the number density and  $\sigma = 4\pi r^2$  is the collisional cross-section. Eq. (2) can be fitted to the binned velocity data, resulting in a coefficient of restitution of  $\varepsilon = 0.64$  (see solid line in Fig. 7a). Thereby, the data represent an average over all impact parameters (i.e. central to grazing impacts) and, thus, collisions are only analyzed statistically, but not as individual binary encounters. The residual of the fit to the data (Fig. 7b) shows a good agreement of both in the interval from 2 to 7 s experiment duration, meaning that the collisional behavior follows Haff's law with  $\varepsilon = 0.64$ . The strong deviation within the first 2 s is due to the equilibration phase of the ensemble after the sample injection, whereas the clear change in slope after  $\sim 7$  s is a real effect that can either be explained by an increased coefficient of restitution towards low relative velocities or the onset of clustering (Goldhirsch and Zanetti, 1993; Brito and Ernst, 1998; Miller and Luding, 2004). However, the investigation of the latter exceeds the scope of this work.

We performed a detailed analysis of individual binary collisions among the constituents of the ensemble in the drop-tower exper-

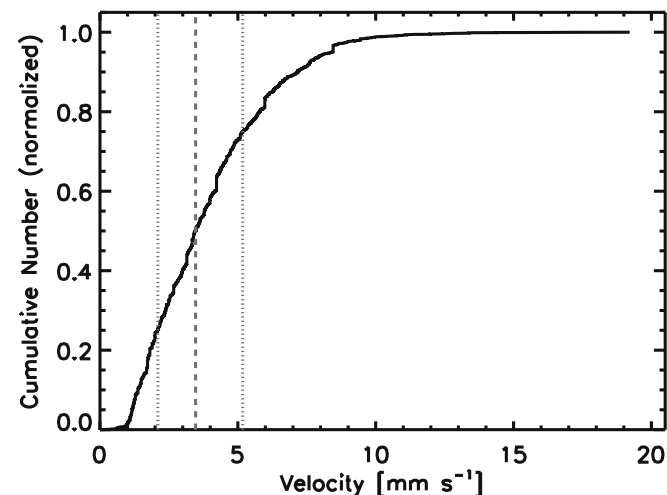


Fig. 6. Normalized cumulative number of glass particles with velocity  $\leq v$  in the time interval of 7–8.5 s of microgravity duration for the drop-tower experiments. The dashed line denotes the median particle velocity and the dotted lines indicate the particle velocities covering 50% of all particles.

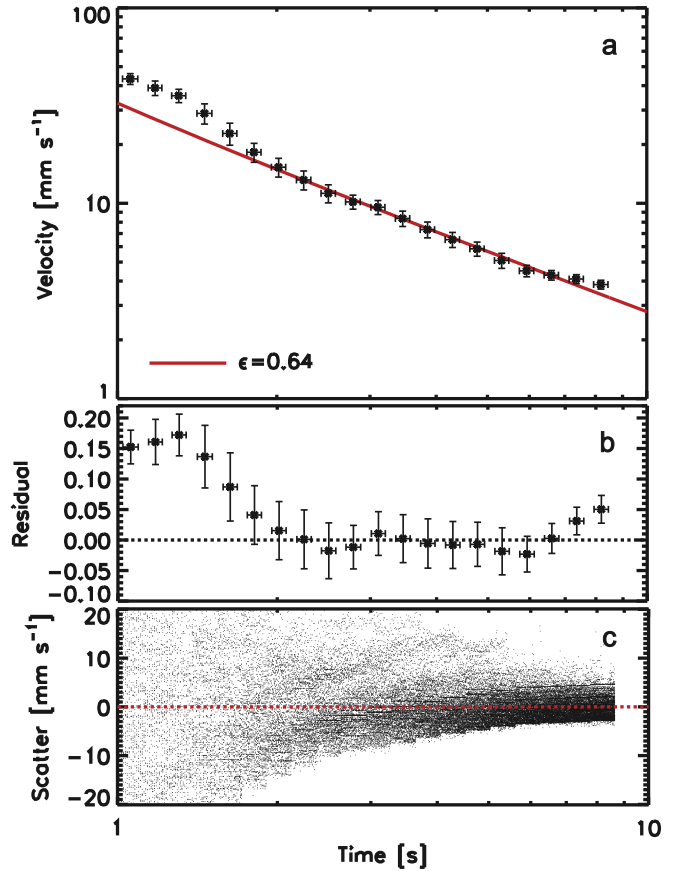
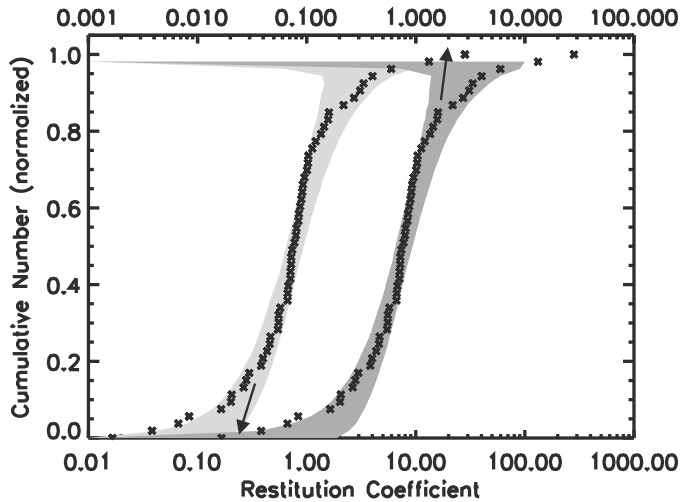


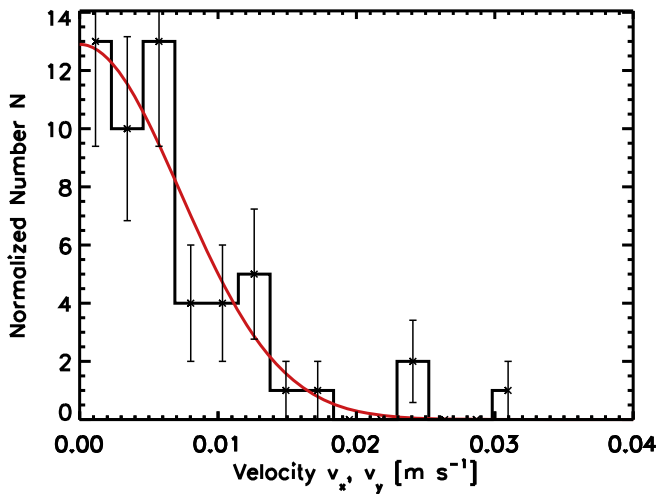
Fig. 7. (a) Velocity decrease of the glass particles in the drop-tower experiment due to the dissipation of kinetic energy as a function of experiment duration. The data was binned in logarithmic intervals. It is clearly visible that after a short period of equilibration the dissipation is in agreement with Haff's cooling law for granular gases (Haff, 1983) between 2 and  $\sim 7$  s experiment duration. The solid line denotes the relation given in Eq. (2) with a coefficient of restitution of  $\varepsilon = 0.64$ . (b) The residual between Haff's law and the data shows a good agreement from 2 to 7 s experiment time. The strong deviation within the first 2 s is due to the equilibration phase after the particle injection, whereas the divergence after 7 s can only be explained by a change of the coefficient of restitution towards low relative velocities. (c) The scatter of the individual data points around the fitted curve shows a broad velocity distribution.

iment as well as of binary collisions of identical glass spheres conducted in a recently built laboratory mini drop tower of 1.5 m height. In the latter experiments we observed 12 central collisions in the velocity range  $1\text{--}4 \text{ cm s}^{-1}$ . The measured coefficients of restitution span a range from  $\varepsilon \approx 0.35$  to 0.95, are randomly distributed (see solid curve in Fig. 5a), and show no correlation with impact velocity.

In the drop-tower experiments with the particle ensemble we have no information about the three-dimensional motion of the particles, so that we are forced to restrict ourselves on the measured two-dimensional projection of the velocity vector before and after the collisions. Splitting the velocity vectors into two one-dimensional components, we can describe the distribution of the absolute velocity values by a one-dimensional Maxwell-Boltzmann distribution function (see right curve in Fig. 8 and solid curve in Fig. 9) with a fixed coefficient of restitution of  $\bar{\varepsilon} = 0.77$ . Using a range of coefficients of restitution, i.e.  $\varepsilon = 0.2 \dots 0.9$ , results in a very similar velocity distribution function (left curve in Fig. 8). The shaded areas in Fig. 8 are the result of a Monte Carlo simulation of a one-dimensional Maxwell-Boltzmann velocity distribution and denote the  $2\sigma$ -range.



**Fig. 8.** The coefficients of restitution obtained by analysis of the binary collisions of cm-sized glass spheres (crosses) can be fitted by a Maxwell–Boltzmann distribution with a constant coefficient of restitution of  $\varepsilon = 0.77$  (right shaded area). Using a range of coefficients of restitution ( $\varepsilon = 0.2 \dots 1.0$ ) results in a very similar velocity distribution function (left shaded area). The shaded areas denote the  $2\sigma$ -standard deviation derived by a Monte Carlo simulation.



**Fig. 9.** The obtained absolute values of the one-dimensional velocities of the binary collisions (histogram with  $1\sigma$  error bars) can be fitted by the positive branch of a Maxwell–Boltzmann distribution (solid curve).

#### 4. Conclusion

In this work, we present first results of two novel experimental methods to study the collision properties of individual macroscopic ice bodies, allowing free encounters without limitations present in previous experiments.

The parabolic-flight setup is suitable for pair-collisions at relative velocities  $\geq 6 \text{ cm s}^{-1}$  and near-central impact angles. For normalized impact parameters of  $b/R = 0\text{--}0.5$  we could not observe a correlation between the coefficient of restitution and the impact parameter nor with the relative impact velocity of ice particles. The fit of a uniform distribution of the coefficient of restitution resulted in a mean value of  $\bar{\varepsilon} = 0.45$ , and a range from  $\varepsilon = 0.06$  to  $0.84$ . The experiments with equal-sized and equal-shaped glass particles with collision velocities of a few  $\text{cm s}^{-1}$  and normal impacts also showed a wide distribution of coefficients of restitution between  $\varepsilon = 0.35$  and  $0.95$ . While for the ice particles one could argue

that surface frost might be responsible for the scatter in the coefficient of restitution this clearly plays no role for the glass beads. Thus, we expect not a single value for the coefficient of restitution for the collisions in Saturn's rings, but a more or less wide distribution around a mean value. Thus, also very elastic and very inelastic collisions concurrently take place in Saturn's rings. The experiments performed by Bridges et al. (1984) and Hatzes et al. (1988) – although investigating central collisions at lower velocities than we did – showed only a weak velocity dependence of  $\varepsilon$  above  $1 \text{ cm s}^{-1}$  with values of  $\varepsilon \approx 0.2$  and  $\varepsilon \approx 0.5$ , respectively, and thereby enclose the results obtained from our parabolic-flight experiments. The experiments by Dilley and Crawford (1996) show a decrease of the coefficient of restitution with decreasing projectile mass and with increasing impact velocities. These results do not match those obtained from our parabolic-flight experiments. Recent works by Grasselli et al. (2009) and Sorace et al. (2009) presenting the investigation of granular cooling and low-velocity binary collisions of mm-sized spherical particles, respectively, report a decrease of the coefficients of restitution with decreasing impact velocities. This finding is supported by the collision model of Brilliantov et al. (2007). This means that it is unlikely that the deviation of our data points from Haff's law (see Fig. 7a) for  $t > 7 \text{ s}$  is due to an increase in the coefficient of restitution. Clustering seems to be a plausible explanation, but needs further exploration.

Recent N-body simulations by Porco et al. (2008) were carried out to create a model of Saturn's A and C ring. This model was used as input for numerical light-scattering studies trying to match the photometric properties observed by Cassini. The authors found that to reproduce their observations with their numerical codes, they required a velocity-dependent coefficient of restitution of  $\sim 3.5$  times lower than that found by Bridges et al. (1984) and five times lower than those obtained by Supulver et al. (1995). These results could not be reproduced by our experiments. However, the presence of surface frost or regolith layers will alter the collisional properties towards more inelastic behavior. A similar trend is known from impact experiments of cm-sized spheres into lunar and martian regolith analog material (Colwell and Taylor, 1999; Colwell, 2003) and low-velocity collision experiments of high-porosity dust aggregates (see e.g. Blum and Münch, 1993; Heißelmann et al., 2007; Langkowski et al., 2008).

In a future microgravity campaign the investigation of ice collisions will be extended to impacts onto a solid ice target and at arbitrary impact angles using a slightly modified parabolic-flight setup.

Using the setup developed as a feasibility study for drop-tower experiments, we were able to achieve collisions between cm-sized glass beads at velocities well below  $1 \text{ cm s}^{-1}$ , which could be fitted assuming a mean coefficient of restitution of  $\varepsilon = 0.64$ . The obtained relative velocities are realistic parameters for simulating the collision processes in Saturn's dense main rings (Esposito, 2002) so that future drop-tower experiments using a cryogenic setup and ensembles of water ice samples will provide further insights into the collision dynamics of icy bodies. These experiments will also incorporate beam-splitter optics to provide three-dimensional collision information, which proved to be of utmost importance for the analysis.

The observed collisional properties, like the coefficient of restitution  $\varepsilon$ , are crucial parameters for theoretical and numerical studies (Salo et al., 2001; Schmidt et al., 2001) aiming to explain observed structures, instabilities and overstabilities in Saturn's dense rings. Additionally, the experiments can be utilized to determine the mechanism of energy equipartition within an ensemble of interacting macroscopic grains. For the explanation of the extremely confined ring thickness and the means to counteract perturbations and excitation by dissipation of kinetic energy, more detailed investigations shall be conducted to study the influence

of regolith-covered surfaces as well as the accretion and chip-off of debris in collisions of icy bodies. If ring particle collisions are dominated by the particles' surface properties and not by their icy cores, a regolith layer will clearly reduce the coefficient of restitution considerably (Heißelmann et al., 2007; Blum and Münch, 1993; Langkowski et al., 2008).

## 5. Future work

In future experiments using a setup similar to the one used for the described drop-tower experiment we will collide ensembles of cm-sized ice particles at cryogenic temperatures. Additionally, low-velocity binary collisions of icy samples will be studied in our laboratory mini drop tower. Both experiments will include stereo optics to gain three-dimensional collision information giving insight into the coefficient of restitution as a function of the impact parameter and the vectorial collision velocity as well as studying the equipartition of translation and rotational energy. The sample properties will also be varied to investigate the effects of surface properties (frost or regolith layers) and shape.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.icarus.2009.08.009](https://doi.org/10.1016/j.icarus.2009.08.009).

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