GRANULAR MECHANICS SIMULATIONS OF COLLISIONS OF DUST-COVERED CHONDRULES.

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Introduction: Chondrules are commonly observed building blocks in Meteorites. They are glassy bodies with sizes up to mm, that probably have been formed out of ejecta of collisions between protoplanets or planetesimals in the protoplanetary disk [1].

After their formation chondrules can accrete a dust rim, that greatly increases the sticking regime for collisions of these chondrules [2].

In this work, we performed Granular Mechanics simulations of chondrules with a dust rim [3]. We present results for bouncing probabilities, ejection yield and energy dissipation. Since our simulated chondrules are much smaller than realistic ones, we furthermore present a simple scaling model, that allows for extrapolation of collision outcomes in other regimes.

Methods: *Granular Mechanics.* We use the Granular Mechanics model as set out in [4]. Particles are described by their radii, positions, velocities and angular velocities. Furthermore, one needs to know a few parameters: density, surface energy, Poisson ratio and Youngs modulus. The model from [4] then gives formulae for contact forces and torques between dust grains: Normal forces (adhesion, elastic and friction), as well as rolling, twisting and sliding torques (all friction).

Collisions. Targets are sampled by setting up a large center sphere (chondrule) and attaching small grains to its surface. Parameters to describe the so built chondrules are the chondrule radius R, the rim thickness d and the filling factor Φ of the rim. To prepare a collision, we set up two such chondrules and boost them towards each other, with relative velocity v. Every collision with chosen parameters (R,d,v) will be performed 10 times with differently oriented chondrules to allow for statistical evaluation.

Results: We evaluate the data in a simple stick/bounce scheme for every collision to obtain a bouncing probability b. Figs. 1 and 2 show plots of bouncing probabilities vs. impact velocity for various chondrule radii and for various dust rim thicknesses, respectively. We also evaluate the ejection yield by performing cluster analysis of the collision results and calculating the mass fraction of the rim, that has been thrown out of the cluster(s) that contain(s) the chondrules. Figs. 3 and 4 show plots of the ejection yield versus rim thickness and chondrule radius, respectively, each for various impact velocities. Figs. 5 and 6 are plots of the power by all forces and torques in the system. Indices fn and fs denote normal and sliding forces, while indices tr, ts and tt denote rolling, sliding and twisting torques, respectively. Overall, we draw the following conclusions from these plots: Bouncing probability increases with impact velocity and chondrule radius, but decreases with dust rim thickness. The ejection yield decreases with dust rim thickness, but does not significantly depend on the chondrule radius. In both sticking and bouncing collisions normal forces are the most important for energy dissipation. Sliding torque excites rotational motion.

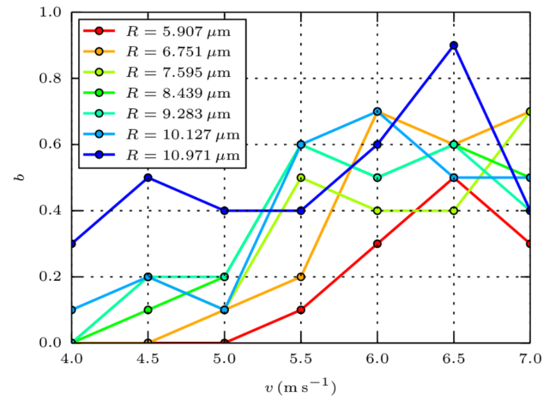

Figure 1: Bouncing probability b vs. impact velocity v for different chondrule radii R.

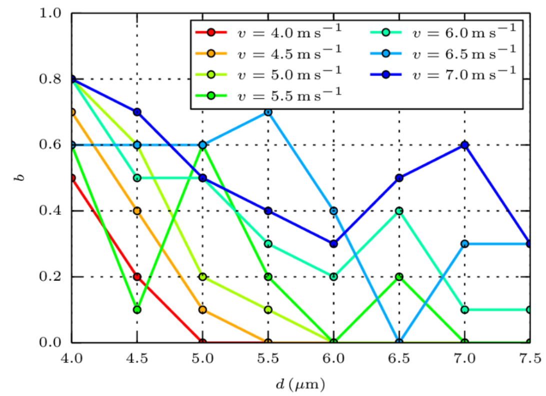

Figure 2: Bouncing probability b vs. impact velocity v for different chondrule radii R.

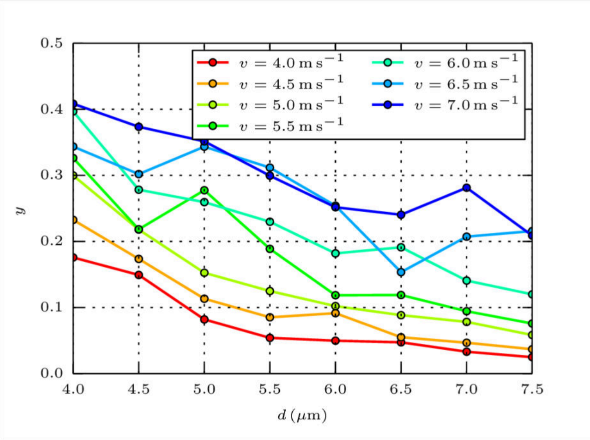

Figure 3: Bouncing probability b vs. impact velocity v for different rim thicknesses d.

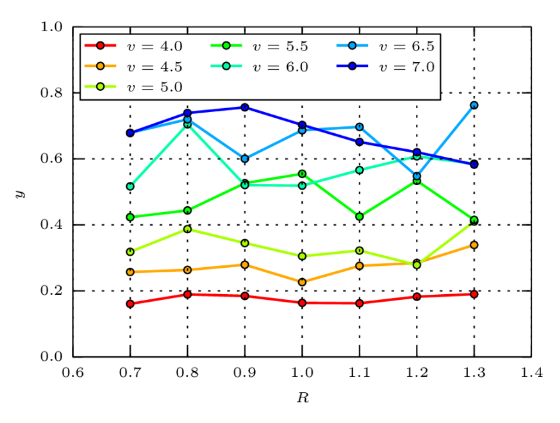

Figure 4: Bouncing probability b vs. impact velocity v for different chondrule radii R.

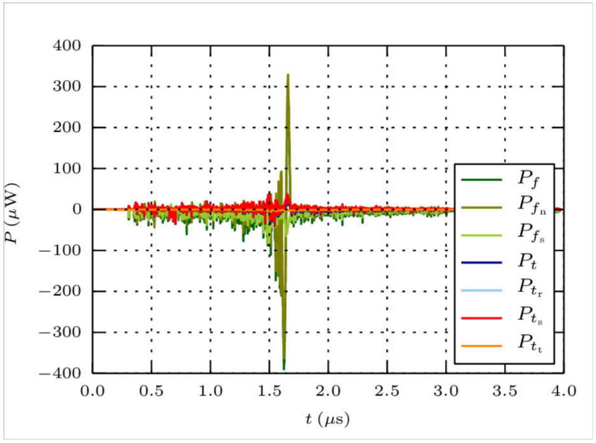

Figure 5: Total power by all forces and torques in the system versus time for a bouncing collision.

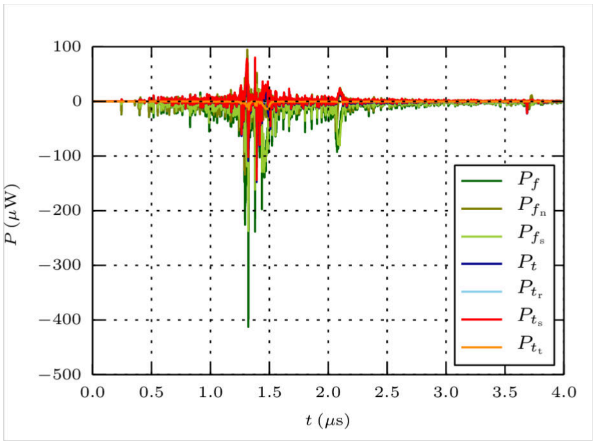

Figure 6: Total power by all forces and torques in the system versus time for a sticking collision.

Scaling Model: To better compare our results with experimental results from e.g. [5], we propose a scaling model as follows. Energy is dissipated by grain contacts close to the impact site. We know how many grain (contacts) are in the spherical caps of height d (rim thickness) and how large the kinetic energy of the collision is. We know a rough estimate of a bouncing velocity (above which more than half of the collisions are bouncing) for our simulations and can therefore calculate an energy per contact that can possibly be dissipated. We propose that this energy per contact is the same for all regimes. For radius r of the grains in the dust rim, this ultimately provides a formula for bouncing velocities in different regimes, which in a simplified fashion can be written as

$$\frac{v_b^x}{v_b^0} = \frac{d^x}{d^0}\frac{R^0}{R^x}\left(\frac{\rho^0}{\rho^x}\frac{\Phi^x}{\Phi^0}\right)^{\frac{1}{2}}\left(\frac{r^0}{r^x}\right)^{\frac{3}{2}},$$

where index 0 denotes an already performed experiment or simulation, while x denotes an experiment or simulation for which one wants to predict an outcome. With this scaling model we indeed see, that our bouncing velocities are in fact not in contradiction to the results in [4].

References: [1] Blum J. (2010) *Res. Astron. Astrophys.*, 10, 1199. [2] Ormel C. W. et al. (2008) *Astrophys. J.*, *679*, 1588. [3] Umstätter Ph. et al. (2019) *Monthly Notices of the Royal Astronomical Society*, 483, 4938. [4] Ringl C. and Urbassek H. M. (2012) *Comput. Phys. Commun.*, 183, 986. [5] Beitz E. et al. (2012) *Icarus*, 218, 701.