# Observing Rubble Pile Dust Impact Dynamics In A Vacuum Environment

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## Introduction

New star systems continue to be observed by the ALMA space telescope. Research into such systems aids our understanding of how planets form. Due to the viscosity of the gas (and the drag this creates on dust particles), an accretion disk can be formed around young stars. The star's planets are formed from the material in this disk. However, turbulence, low gas/dust densities, radiation from the star, drift, and a partially ionized disk environment provide a protoplanetary formation process that is far from straightforward. Fortunately, recent geological research categorizing the interiors of meteorites may provide a record of the environment present during the formation process, allowing one possible mechanism for measuring the powerful dynamics in the protoplanetary disk environment. 80% of meteorites contain the centimeter-sized pebbles (chondrules) that comprise 60% to 80% of the rock's composition. Covering most chondrules is a rim of fine micrometer-sized dust. This fine-grained rim (FGR) differs from the surrounding matrix in both the size of the dust grains and the structural porosity. An even more curious observation is supported by a geological technique for extracting 3D models of chondrules and their rims from chondrites developed by R. Hannah [1]. Hannah showed that the chondrule rim size is correlated to the radius of the chondrule itself rather than the cementing matrix or size of the meteorite. She accomplished this using an experimentally determined linear fit $\Delta r \approx 0.1a_0 + 26$, where $a_0$ is the chondrule radius and $\Delta r$ is the size of the dust rim. The '26' is a surprising constant that appears in the linear fit. Together, these observations suggest that FGRs did not form inside the more extensive body but rather around the chondrule before it aggregated into the larger body. Therefore, a proper understanding of how such rims form offers critical information to our understanding of the development of the protoplanetary disk environment. There are two specific variables to consider when seeking to understand FGR development. The first is the relative velocities of the particles and chondrules which are controlled by coupling between the particles and the gas. The

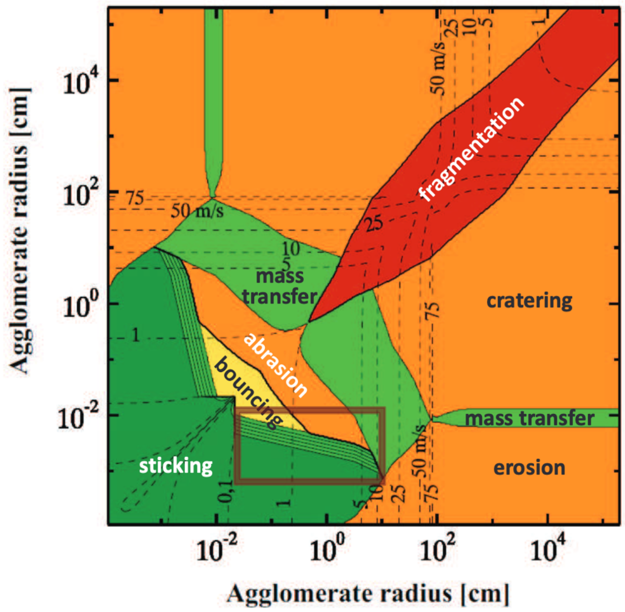


Fig. 1: Collision outcome graph based on the size of the dust aggregates involved in the collision. The black dotted lines indicate the impact velocity in m/s. [4]

second is the size of the particle or particle agglomerate that impacts the rim. Using a hydrodynamical understanding of the protoplanetary disk put forth by Weidenshilling [2], Ormel created a theoretical model that demonstrates the formation of chondrule rims around cm-sized particles at low (i.e., below one m/s) relative collision velocities [3]. Subsequent experimental work by Blum and Wurm on protoplanetary growth is shown in Figure 1. The region in the red box displays the uncertainty surrounding the transition region between bouncing, abrasion, and sticking for micron-sized agglomerates colliding with a larger bed at low velocities. It is assumed that FGR formation occurs in this velocity regime which would appear to validate Ormel's conclusions. However, this does not address the high degree of compaction observed on rims, the apparent erosion present on the surface of most chondrules, or the resulting constant provided by the correlation between the chondrule radius and the thickness of its rim. These objections are a focal point of Liffman's 2019 paper [5]. He proposes that some event accelerated a percentage of the chondrules in the protoplanetary disk which were then exposed to dust traveling at a spectrum of speeds as the chondrule re-coupled to the gas and dust. It is assumed these collision speeds exceeded the equilibrium velocity where erosion of the chondrule surface has been observed. As such, equilibrium velocity deposition of dust particles (i.e., kinetic dust aggregation) could occur, resulting in a more compact rim composed of smaller particles. As these collisions slowed past some critical velocity, the resulting aggregation reverted to a result in agreement with Ormel until fluffy aggregation of dust with "hit and stick" collisions (i.e., dust hitting the surface while not causing any restructuring) dominated.

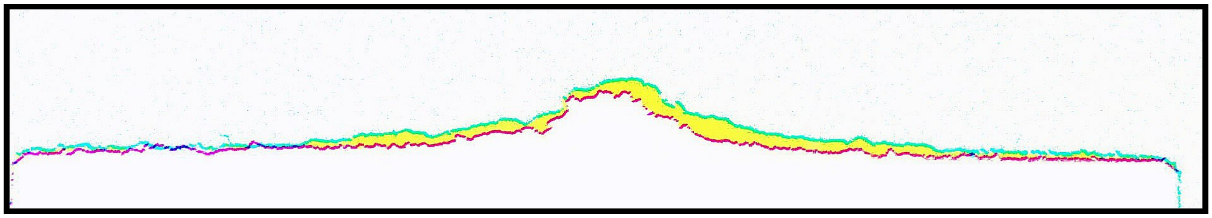

Fig. 2: Side view of the progression of the rubble pile contour after many dust drops using 20-micron spherical alumina dust. The bottom contour (Red) was created with dust traveling at approximately 0.24 m/s, and the top contour (white) was created by dropping dust at 0.8 m/s on top of the first structure.

**Experiment**

In order to properly study dust aggregation before the meter barrier is overcome, observation of dust layering on the surface of a particle is required across all the velocity spectrums discussed above. This research accomplishes this by combining theoretical, observational, computational, and experimental work to examine the question of dust aggregation onto the surface of a chondrule analog. The experiment discussed below was carried out in a GEC reference cell at a pressure of 10E-5 Torr. 20-micron spherical alumina dust was used for velocities ranging between 0.28 m/s and 1.4 m/s. The resulting formation of a dusty surface was captured using imaging process techniques. The effects of varying the dust velocity can be seen in figure 2, where the image shows the evolution of the dust pile contour taken by the side camera. As shown, the original structure exhibited jagged edges created by "hit and stick" collisions. The top contour is affected by the jagged structure of the first but the surface is smoother due to the increased impact energy of the dropped dust. Also, clumping was more prevalent toward the top of the Surface.

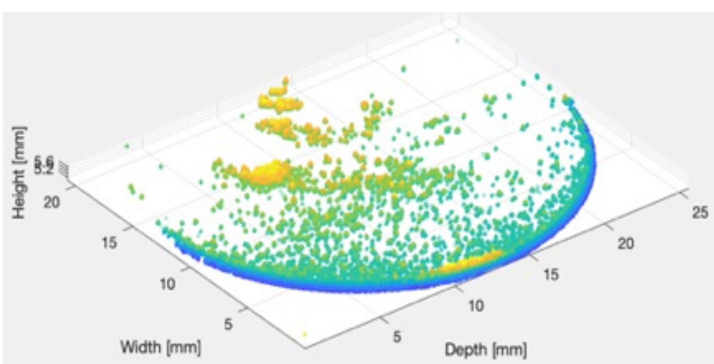


Fig. 3: The 3D virtual representation of the surface created from laser scans of a rubble pile created in the lab.

**3D Representation**

To track small changes to the pile structure, height and depth information from the rubble pile is needed on a particle scale. The technique used here provided results listing 3D attributes of the pile. This 3D map consisted of 2D slices of the pile stacked on one another. When performed for each successive

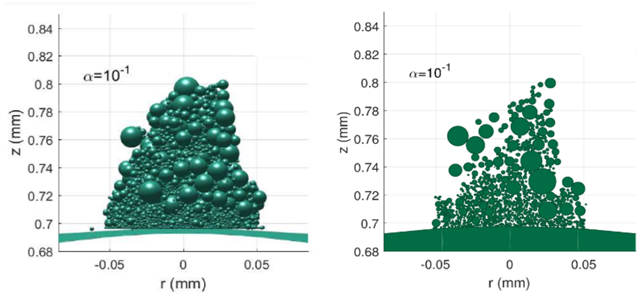


Fig. 4: Simulation results from C. Xiang et al. The left image is a 3D representation of the 'monomer pile' comprising the FGR. The right image is a vertical 2D slice of this 3D structure. [6]

drop, this resulted in a time-lapse data of the surface evolution as additional dust was dropped onto the surface. A representative frame is displayed in figure 3 with the scale of the experiment shown.

C. Xiang has recently provided numerical research along this line [6]. Using Ormel's protoplanetary dust model [3] and the numerical work of A. Carballido [7] to determine protoplanetary disk parameters, her numerical simulation maps dust particles of various sizes and speeds interacting with a chondrule surface. The resulting 'monomer pile' is shown in figure 4. The left image provides a 3D representation of the pile, with the right image a vertical 2D slice of this 3D structure. In the 2D slice, the porosity of the pile is evident. This project has the ability to look at the contours of dust structures that form on a surface in a similar fashion to her numerical analysis, providing her with experimentally determined results to support and refine her numerical technique.

**Conclusion**

The ability to resolve individual dust particles on a surface to track agglomeration on that surface has been demonstrated. This data allows for the investigation of dust clumping and the heights obtained by the piles under different parameters, including the impact speed of the dust particle, size, and charge. In future experiments, both dust material and target material will be varied. Observation of the particle behavior around the transition boundary from "hit and stick" to "bouncing/abrasion" interactions will aid the ongoing numerical work. Utilizing these tools, dust impacts between 2 and 10 m/s and the evolution of surfaces affected by these impacts will be examined.

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