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Microgravity Experiments on Accretion in the Protoplanetary Disk

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ABSTRACT: We present the results of an experimental investigation of low-energy collisions between cm-scale and smaller particles in the protoplanetary disk to better understand conditions conducive to the growth of planetesimals, the km-sized building blocks of planets. The COLLIDE (Collisions Into Dust Experiment) and PRIME (Physics of Regolith Impacts in Microgravity Experiment) programs involve cm-scale projectiles impacting a target bed of unconsolidated granular material in microgravity environments on Space Shuttle missions and parabolic airplane flights, respectively. In these experiments, a portion of the target material adhered onto the impactor in some low-velocity impacts (<40 cm/s). Such impact speeds are too slow to study in a normal gravity environment (1 g, where $g = 9.8$ m/s² is the acceleration due to gravity on the surface of the Earth). Factors including ambient air pressure, impactor mass and composition, impact velocity, and particle composition may affect the occurrence of mass transfer. We designed and built an apparatus that made use of a laboratory drop tower to obtain a brief (0.7 s) microgravity environment during free fall at standard atmospheric pressure. The laboratory drop tower does not provide enough time to study impact and rebound of a projectile at impact speeds of less than 1 m/s, so we designed our apparatus to simulate only the rebound portion of a collisional event. We suspended a marble from a spring with the marble resting on a bed of granular material in 1-g. During free fall, the spring pulls the marble away from the granular material at a low acceleration, simulating rebound of a projectile. Because the spring continually accelerates the sphere away from the granular material, the rebounds are characterized by an acceleration rather than a rebound velocity. We obtained rebound accelerations from ~ 1 –6 m/s², and we observed mass transfer at accelerations below 4 m/s². Mass transfer events such as these indicate one potential growth mechanism for the building blocks of planetesimals.

KEYWORDS: mass transfer; microgravity; low-velocity; collision; acceleration

INTRODUCTION

According to nebular theory, our solar system began as a cloud of dust and gas called a solar nebula. The solar nebula collapsed under its own gravity with most mass eventually becoming the Sun and a disk of gas and dust surrounding the new-formed star (e.g. Weidenschilling and Cuzzi 1993). Low-velocity collisions between dust particles in this protoplanetary disk allowed them to stick together due to electrostatic forces in a process known as collisional accretion (e.g. Blum et al. 2000). The growth of 1-100 km-sized planetesimals may have occurred through gravitational instabilities, collisional accretion of these cm-scale dust aggregates, or some combination of the two processes depending on local nebular conditions (Michikoshi and Kokubo 2016). The gravitational attraction between planetesimals is large enough to allow them to grow into planets (e.g. Greenberg et al. 1978). The growth from cm-scale “pebbles” to km-scale planetesimals has remained the subject of active research due to the challenges faced by both collisional models and gravitational instabilities (see Wurm and Blum 2008 for a review).

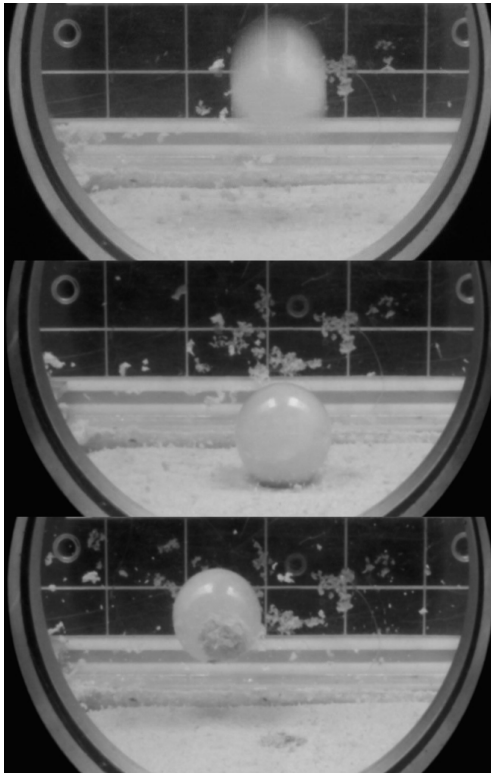


Figure 1: Still frames of a quartz projectile in COLLIDE before, during, and after (respectively) impact into quartz sand at 26.5 cm/s with observable mass transfer.

Research on accretion in the protoplanetary disk has revealed that specific conditions are necessary for accretion to occur efficiently. Factors including the relative velocities and the sizes and compositions of the colliding particles can determine whether the interaction results in destructive shattering or growth through accretion (Benz 2000). The study of low-velocity collisions of small particles in negligible gravity provides insight into the specifics of this process. Experiments conducted on orbit, in suborbital space, and in parabolic airplane flights that provide a low gravity environment, like the Collision into Dust Experiment (COLLIDE, Colwell and Taylor 1999, Colwell 2003) and the Physics of Regolith Impacts in Microgravity Experiment (PRIME), have demonstrated the process of mass transfer (Colwell et al. 2008, Brisset et al. 2016). An example of this process is shown in Figure 1, in which a 2-cm-diameter projectile collided with a target bed of granular material at a low velocity (26.5 cm/s) and a significant portion of granular material adhered to the surface of the projectile.

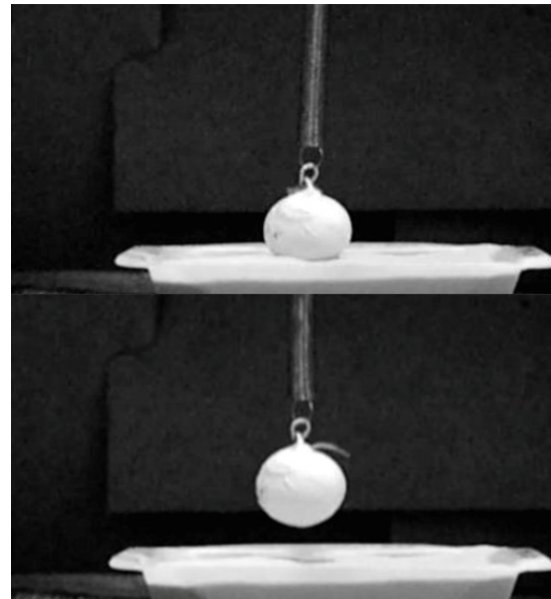


Figure 2: Still frames of a Teflon-coated brass marble during and after (respectively) impact into quartz sand at 34 cm/s at 1 atm and 1-g with no observable mass transfer (Jarmak et al. 2016).

Our preliminary laboratory-based experiments suggest that mass transfer does not occur in a normal laboratory gravitational environment (Jarmak et al. 2016). Some trials in 1-g resulted in only a monolayer of granular material transferring onto the projectile. Figure 2 shows still frames of a trial conducted at 1-g, in which a cm-scale projectile collided with a target bed of granular

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material at a low velocity (34 cm/s): no mass transfer was observed. The gravitational pull from the Earth overcomes the weak interparticle forces that can adhere the granular material onto the impactor.

To systematically investigate the process of mass transfer of granular material onto a cm-scale projectile observed in COLLIDE and PRIME, we designed an experiment to study collisions between projectiles and various types of granular material in a ground-based microgravity environment. Our goal was to gain an understanding of the conditions in which mass transfer was most likely to occur. In this paper we present the findings of these trials and discuss their implications.

METHODS

Observations of mass transfer in COLLIDE and PRIME were made during flight-based experimentation, which allowed us to make our observations for extended periods of time in a microgravity environment as well as in a vacuum. To achieve a microgravity environment in ground-based trials, we used a laboratory drop tower: a 3.7-m tall apparatus from which we could drop an experimental payload. The drop tower allows for ~0.7 seconds of a microgravity environment in free fall during which we could conduct experiments. This setup does not provide sufficient time to observe the full extent of an impact and rebound collision event at the low impact speeds necessary for mass transfer. Therefore, we designed an experimental chamber to simulate only the rebound of a projectile. Figure 3 provides a graphic representation of the experimental apparatus. We suspended a marble from a spring and let it rest in a bed of granular material prior to dropping it in the drop tower. We carried out our experiments using JSC-1 lunar regolith simulant (McKay et al. 1994) and quartz sand (Table 1).

Material Type	Grain Size (μm)
quartz sand	75 - 250
JSC-1	125 - 250
	250 - 500

Table 1: Granular Materials

In a 1-g environment, the weight of the marble caused the spring to stretch away from equilibrium while the marble remained in contact with the bed of granular material. When the payload was in free fall, the spring

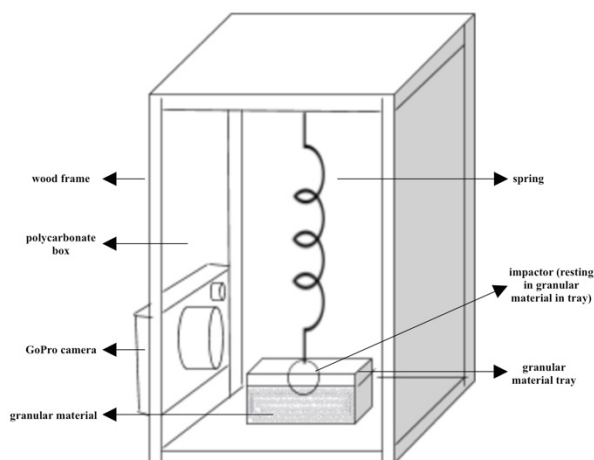


Figure 3: Schematic of the experimental apparatus, consisting of a marble suspended by a spring in a bed of granular material. The spring pendulum system is encased in a polycarbonate box with a wooden frame and an attached video camera.

retracted, lifting the marble out of the bed of granular material. This setup effectively simulated the rebound of a collision similar to those observed in flight-based experiments. In prior flight-based experiments, collisions caused the projectile to compress the granular material at the point of contact before it rebounded. To control for this variable, spring lengths were chosen such that a minimal amount of weight was supported by the granular material in 1-g. The weight of the marble supported by the granular material in 1-g is given in Table 2. The granular material was poured gently into the container before each trial, and the marble was placed onto the top layer as lightly as possible.

We attached a *GoPro Hero 3+* camera to the apparatus as shown in Figure 3, which provided video at 240 frames per second with a 420p resolution for each trial. We tracked the frames from these videos using the program ImageJ (Rasband 1997-2016), an open source image processing package, to measure the rebound acceleration of the spring system. To enhance the visual contrast between the marble and granular material for tracking purposes, we coated the steel marble with white Teflon spray during the JSC-1 trials, and we tinted the quartz marble with black ink for the quartz sand trials. We tracked the motion of the marble in each video multiple times to confirm consistency in our measurements. We were able to qualitatively determine the presence or absence of mass transfer in each trial.

In addition, we varied the acceleration of the marble

away from the target surface by using marbles (1.9 cm diameter) with variable masses and springs with different spring constants and lengths as shown in Tables 2 and 3.

Marble Material	Marble Mass (g)	Marble Mass in Granular Material (g)
steel	39.1	19.0
quartz	11.5	2.2

Table 2: Marble Materials and Masses

Spring Constant (N/m)	Spring Length (cm) ± 0.01
1.93	20.0
1.96	18.0
2.43	14.0
2.51	13.0

Table 3: Spring Constants and Lengths

We chose combinations of spring constants and marble masses to allow for sufficiently slow rebound velocities and thereby maximize the opportunity for mass transfer to occur. We performed calculations with the equations of elastic potential energy and kinetic energy to determine these parameters. In equations (1-4), PE is potential energy, k is spring constant, x is the displacement of the spring from equilibrium, KE is kinetic energy, m is marble mass, v is velocity, and E_{total} is total energy:

$$KE = \frac{1}{2}mv^2 \quad [1]$$

$$PE = \frac{1}{2}kx^2 \quad [2]$$

$$E_{total} = KE + PE \quad [3]$$

The velocity of the marble after the spring has returned to its equilibrium position is given by:

$$v = \sqrt{\frac{kx^2}{m}} \quad [4]$$

As soon as the apparatus is dropped, the marble begins accelerating away from the surface of the granular material with an initial speed of zero. In the long-duration microgravity experiments of COLLIDE-3 and PRIME-3 (Brisset et al. 2016), there was sufficient time for the marble to strike the target and rebound at lower speed, potentially carrying some accreted target material with it. The spring mechanism used in this experiment results in the marble accelerating away from the target surface instead of moving away at a constant rebound velocity. Therefore, these laboratory-based results cannot be directly compared to long-duration flight experiments. Instead of characterizing the rebound event by the marble velocity, we measure the acceleration of the marble away from the surface. We then characterize the acceleration of the rebounding projectiles in the flight-based experiments using a simple impulse approximation. To measure the acceleration of the marble, we first track the change in the marble's position. From the change in the marble's position over time we can measure the velocity as a function of time and calculate the acceleration from the rate of change of the velocity. We measured accelerations between approximately 1 and 6 m/s². For comparison, we estimate the acceleration of the projectile in COLLIDE (Figure 1) to be 1.3 m/s² by simply taking the rebound velocity minus the impact velocity divided by the time of contact with the target material.

RESULTS

We conducted 34 trials, 10 of which resulted in observable mass transfer. The amount of mass transferred in these trials (Figures 4 and 5) was visually more significant than the monolayer of granular material transferred in 1-g testing, but also consistently less than the mass transfer observed in COLLIDE and PRIME during flight-based experiments (Figure 1).

Because rebound velocity is not well-defined with the spring mechanism attached to the marble, we focused on the relationship between rebound acceleration and observed mass transfer. We observed mass transfer only in trials with rebound accelerations from ~1.00 – 4.00 m/s² (Figure 6). Mass transfer was observed within this

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acceleration range for both quartz sand (75-250 μm) and JSC-1 (250-500 μm).



Figure 4: A steel marble rebounding from quartz sand at 2.48 m/s^2 with observable mass transfer.



Figure 5: A Teflon-coated steel marble rebounding from JSC-1 at 2.34 m/s^2 with observable mass transfer.

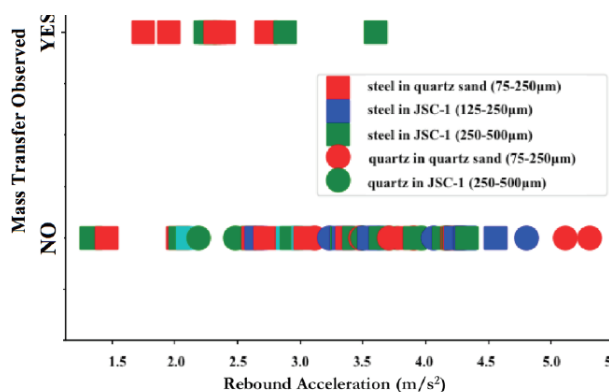


Figure 6: Mass transfer events observed for various granular materials, marbles, and rebound accelerations.

Table 4 shows the specific rebound accelerations at which mass transfer was observed in trials using various granular material simulants.

Granular Material Type / Grain Size (μm)	Acceleration (m/s^2)
quartz sand (75-250)	1.41
	1.60
	1.94
	2.45
	2.48
JSC-1 (250-500)	2.34
	2.54
	3.59
	4.33

Table 4: Rebound Accelerations at which Mass Transfer was Observed for Various Granular Materials

DISCUSSION

We have demonstrated that accretion events in the protoplanetary disk can be experimentally studied in a laboratory-scale drop tower. Further experiments will enable a detailed exploration of the parameter space of collisions like those that occurred in the early stages of planetesimal formation. Low-velocity (<10 m/s) collisions between small (μm - cm scale) bodies are common in early stage protoplanetary disks and planetary ring systems. In the absence of significant gravity from larger bodies, acceleration in these interactions should be minimal (Weidenschilling and Cuzzi, 1993). Thus, the acceleration values obtained in this experiment and its predecessors are likely comparable to those found in collisions between small bodies in protoplanetary disks and planetary rings.

We aimed to determine a relationship between the occurrence of mass transfer events and granular material properties. While mass transfer was observed in trials with both quartz sand (75-250 μm) and JSC-1 (250-500 μm), a full range of accelerations was not achieved in trials with each type of granular material and grain size. We achieved rebound accelerations between 1.00 and 1.99 m/s^2 only in trials using quartz sand, and rebound accelerations between 3.00 and 5.99 m/s^2 only in trials using 250-500 μm JSC-1, so a comparison between granular materials within these acceleration ranges could not yet be drawn. We plan to conduct more experiments

using these and other granular materials within the current acceleration parameters, which will allow us to establish a more conclusive understanding of this relationship.

We compared acceleration values obtained in PRIME (in which full impact and rebound collisions were studied) with the acceleration values obtained in ground-based experimentation using the spring-retraction rebound mechanism. Table 5 shows the rebound accelerations of trials in which mass transfer was observed in PRIME, which were on average an order of magnitude smaller than the rebound accelerations obtained in this experiment.

Granular Material / Grain Size (μm)	Acceleration (m/s^2)
quartz sand (75-250)	0.09
	0.14
	0.38
JSC-1 (250-500)	0.17
	0.20
	0.30
	1.40

Table 5: Rebound Accelerations at which Mass Transfer was Observed for Various Granular Materials in PRIME

Given this observation and our goal of determining conditions in which mass transfer is most likely to occur, we plan to adjust our experiment design to minimize acceleration of the marble as it retracts from the granular material. This will allow us to probe lower rebound acceleration ranges as seen in prior flight-based experiments and broaden the parameter space covered by our data, as well as explore the effect of rebound velocity on mass transfer events. We plan to replace the current spring mechanism with a wire attached to a wheel on a servo motor, which will turn to retract the wire and attached marble at a constant, low velocity. This adjustment to our experimental design will allow us to target velocity and acceleration ranges with more precision and compare our observations more directly to observations of prior experiments.

Compaction of the top layer of regolith due to the mass of the marble may affect the quantity of mass transfer as well. In future experiments, we plan to explore this

relationship by conducting trials within the same acceleration space using projectiles with larger masses and sizes.

CONCLUSIONS

We have shown that mass transfer is possible in low-acceleration ($<5 \text{ m/s}^2$) interactions between small particles (μm -cm size) in a laboratory-based microgravity environment at standard pressure. The observation of more significant mass transfer in this experiment than in the 1-g experimental analogue reinforced the importance of a microgravity environment for the occurrence of mass transfer. However, the amount of mass transfer we observed in this experiment was less significant than the mass transfer observed in COLLIDE and PRIME, which suggests that differences between these experiments may be critical to the occurrence of mass transfer. It is also possible that compression of the regolith due to the mass of the projectile plays a role in the mass transfer process.

The data presented here suggests that there may be an inverse relationship between rebound acceleration and the likelihood of a mass transfer event. We observed mass transfer only in trials with rebound accelerations below 5 m/s^2 , the majority of which had rebound acceleration values below 3 m/s^2 . However, it should be noted that the acceleration parameter space was not covered equally by the trials conducted, so further trials must be conducted before a more robust conclusion can be made regarding the relationship between rebound acceleration and the likelihood of a mass transfer occurrence.

In future work, we plan to modify our experimental apparatus so that we can conduct trials in a vacuum environment. This will allow us to explore the relationship between ambient air pressure and mass transfer, and make our data more comparable to that of previous experiments. We also plan to probe lower acceleration rebound parameters using more massive marbles and the more precise control provided by the new servo-retraction rebound mechanism.

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