EXTRA LOW-GEAR: A MICRO-GRAVITY LABORATORY TO SIMULATE ASTEROID SURFACES. D.J. Scheeres, *U. Colorado, Boulder (scheeres@colorado.edu)*, P. Sánchez, *U. Colorado, Boulder*, R.W. Dissly, *Ball Aerospace*, E.I. Asphaug, *UC-Santa Cruz*, K.R. Housen, *Boeing*, M.R. Swift, *Nottingham University*, H. Yano, *JAXA/ISAS*, S.E. Roark, *Ball Aerospace*, J.C. Soto, *Ball Aerospace*.

The conceptual design and application of a low-speed centrifuge for carrying out milli to micro-G gravity experiments to simulate the granular nature of the surface and interiors of asteroids and comets is described. The proposed device is well suited for the Human-Tended Suborbital Science program as its 3-5 minute weightless durations are sufficient to successfully simulate the surfaces and interiors of small bodies and carry out granular dynamics experiments. The device is also safe to use in close quarters as the maximum rotation rates are less than 3 revolutions per minute, so for a 1 meter diameter wheel the speeds of the edges will be less than .16 m/sec. The granular materials will be encased within the separate experiment chambers, ensuring that they will remain contained throughout the sub-orbital flight.

Scientific Significance Dry granular materials are ubiquitous in nature and exhibit a wide range of nontrivial dynamical behaviors which are intensively studied in many different types of systems and excitation conditions, both experimentally and theoretically, under the constraint of a constant gravitational field of $1G$. With our proposed device it becomes possible to explore granular particle mechanics in extremely low gravitational environments that have not been explored. The physics and mechanics of such flows are poorly understood, yet exert significant influence over small bodies. Clear examples of this can be inferred from spacecraft observations of small bodies, such as Eros and Itokawa, where their morphological features were seen to be dominated by granular material. The application of the proposed laboratory goes well beyond the study of asteroid surfaces, and can also shed insight and perform relevant experiments to better understand the physics and thermodynamics of asteroids and comets. The proposed device can also enable exploration of a realm of physics not attainable on the Earth, yet which is of extreme importance in understanding the early formation and evolution of planetesimals. By performing fundamental experiments it can be used to identify fundamental physical processes and calibrate numerical codes developed for studying all of these phenomenon. The device can also be used for the design of rover and exploration vehicles designed for operation on a comet or asteroid surface. Due to the extremely low gravitational accelerations it is necessary to develop alternate approaches to locomotion, which require testing for technological risk reduction. The proposed laboratory can be used for testing critical elements and technologies for such vehicles.

Conceptual Design The gravitational acceleration at the surface of a body can be estimated as: $g \sim \frac{4\pi}{3}\mathcal{G}\rho R$ where $\mathcal{G} \sim 6.672 \times 10^{-8}$ cm^3/g/s^2, ρ is the bulk density in g/cm^3, and R is the body radius. If we assume a bulk density of 2 g/cm^3 we find that $g \sim 5.6 \times 10^{-7} R$ m/s^2, where R is measured in meters. Thus for bodies with mean radii ranging from 100 to 100,000 m the surface gravity will range from 5 micro-G to 5 milli-G (1 G = 9.81 m/s^2). The rotation of the body will further decrease the effective gravitational acceleration, although for most small bodies this reduction is just a fractional adjustment to the surface gravity.

In a weightless environment it becomes possible to generate this range of accelerations using a simple centrifuge design. For a centrifuge with radius r and spin rate ω an object at the floor of the centrifuge will experience a net centripetal acceleration of $a \sim \omega^2 r$. For an experiment to simulate the surface environment on a small body of radius R, the spin rate of the apparatus must be chosen to be $\omega \sim 7 \times 10^{-3}\sqrt{\frac{R}{r}}$ revs/min. For a centrifuge with a radius of 0.5 meters the necessary spin rate to cover the stated range of small body sizes then ranges from $0.1 \rightarrow 3$ revs/minute, a very modest yet controllable spin rate.

In a low-gravity environment a crucial limiting factor is the time it takes for a perturbed granular flow to settle. This is controlled by the height to which a granule is excited and the simulated level of gravity. The necessary excitation speed of a particle to reach a given height, h, is $\dot{h} \sim \sqrt{2hg}$ and the corresponding settling time is $T_s \sim 2\sqrt{2h/g}$. Thus for an experiment at $g \sim G \times 10^{-3}$ and a particle shaking height of 1 cm we find a necessary excitation speed of 1.4 cm/s and settling time of less than 3 seconds. Such an excitation speed can be generated by vibrating a platform an amplitude of a few millimeters with a 10 Hz frequency. Such considerations also control the deposition of particles and impact speeds. For an experiment at $g \sim G \times 10^{-6}$ the corresponding excitation speed and settling time for a height of 1 cm is on the order of 0.5 mm/s and 1.5 minutes. Here, the use of smaller grains can allow a scaled experiment to be developed with smaller excitation heights and shorter settling times. Reduction of the excitation height by an order of magnitude (implying the use of grains an order of magnitude smaller) cuts the settling time by a factor of 3. Such scaling can be applied to the experiment to enable useful experiments to be carried out in the allotted 3-5 minute period.

Conceptual Laboratory Design Our current design of the Extra Low GEAR laboratory includes a controllable centrifuge with four chambers. Each chamber will be capable of holding a small payload of grains with varying size, a monitoring camera, a deposition device mounted towards the center of the centrifuge, and a vibration device on the floor. The centrifuge, payload, camera, shooter, and miscellaneous components will be contained in an enveloping housing capable of being evacuated to a low vacuum of approximately 5 Torr to minimize atmospheric effects and also to contain all the experiment components. A possible configuration for such a centrifuge is shown in Fig. 1.

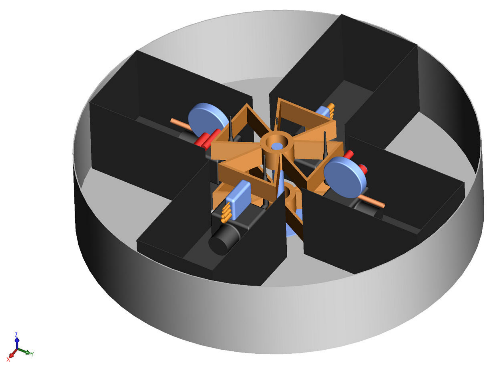

Figure 1: An example configuration for the Low-Gear Experimental Apparatus

Scientific Experiments Driving the development of this device are a series of specific granular mechanics experiments that can be explored with such a laboratory.

Granular Piling: The most common way to aggregate grains is as a pile. It is also known that when the slope of the pile exceeds a “critical angle” or “angle of repose,” an avalanche takes place so that the slope is reduced and the configuration of the pile is more stable. Recent efforts have been made to understand how cohesion affects the stability of granular slopes [7] (and references therein). If an extremely small, non-uniform gravitational pull is the only force present to coalesce the particles, how this will affect the surface friction and stability of the pile is a question of relevance. An experiment to investigate this effect, and carried out with the apparatus described herein, would place the beads inside a cylindrical container which longest axis coincides with the radius of the apparatus. This will give us a degree of control over the Coriolis effect and flow rate of beads forming the pile. The results from this experiment will be useful to study the evolution of asteroid surfaces and validate their simulation [4].

Seismic waves: Granular aggregates are far from being continuous, and as the material is compressed they are expected to have better wave transmission. Work on how waves travel in granular materials has already being carried out for many years [3] due to their importance in earthquakes [2]. More recently, efforts have also addressed the non-linear behavior of seismic waves in granular materials [6]. However, the physics of these effects under a very small gravitational pull has not been addressed. For this experiment we can work with larger beads which gives us the opportunity to have a sensor as big as one of the beads so that we can visually trace it and also get a signal that can be used to track the wave. The experiments should be carried out at different values of gravity to measure the differences. The results from this experiment will shed light on the effect that collisions have on asteroids and provide information for the interpretation of the interiors of asteroids.

Force chains: When on the surface of an aggregate of grains a large object is supported through force chains, something that has already been analyzed through impact dynamics [1] (and references therein). How much such an object sinks should then depend on how strong these chains are. If chain forces are formed due to the stress in the aggregate [??], the sinking of the object should be inversely related to the “gravitational” pull. The experiment should be carried out with beads made out of a photoelastic material, so that their deformation, due to the bearing of a heavy object or impact on top of the aggregate, is evident under polarized light. The experiments should be carried out under a range of gravity values so that comparison and analysis is possible. Pressure sensors should be attached to the walls of the container to have a better understanding of the stress induced into the aggregate. The results from this experiment can help us to further understand the transport and support of larger boulders on asteroid surfaces.

Other experiments to investigate phenomena such as low speed collision dynamics, cohesion and low speed impacts, evolution of compaction [5], and gravitational dependence for phase transition could also be addressed by appropriately using the apparatus described in this abstract.

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