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Title: **Moon-Drop-Shot**

Introduction - Impact into soft, particulate matter occurs on many length scales, ranging from bullets hitting a sand bag or a raindrop hitting soil, to important astrophysical processes, like interplanetary dust particles impacting a slowly growing asteroid. Such impact dynamics can be very revealing of the nature of the interparticle forces or the collective mechanics of the granular material [1-3]. Lunar impact experiments provide a unique opportunity to learn more about the basic science of impact dynamics, which is also a fundamental process in space physics. At the same time such experiments can reveal much about the collective flow behavior of regolith, without the need of bringing significant samples back to Earth. Here we outline how such experiments can be realized on the Artemis mission.

Methodology - Lunar impact experiments require very minimal equipment. A human lunar explorer would only have to drop small spherical objects of diameter **D** from different heights **H** on the lunar soil surface – see Figure 1. The spherical object can function as an independent unit, equipped with the required accelerometers, gyroscopes and data recording equipment. Even the power-up phase of the sensor can be entirely automated. Data can be transmitted wirelessly from the impactor to an external storage platform after experiments have been concluded, or they can be retained on the device itself. The technology for making sensor-laden impactors is already developed. For example, one of the members of the current team Baltus has led the EU funded project "Phoenix" [4] in which an entire hard/software platform called Smarble is developed. Smarbles are smart sensors that can be customized to a great extent and equipped with the necessary sensors, such as high sensitivity accelerometers, gyroscopes, magnetometers and data storage and transmission components [5]. An optional addition to the experiment is high-speed video recording, which could provide information about regolith flow dynamics.

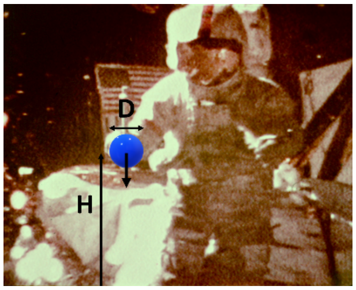

Figure 1: lunar explorer dropping spheres of different size from different heights on the lunar surface. Photo copyright NASA.

Basic Science Impact - Over the past two decades, an array of laboratory experiments on dry granular media and particle-fluid mixtures have helped us understand aspects of the such impact dynamics especially for moderate speed impacts. However, most of these experiments are dominated by gravitational forces. For example, the depth-dependent static forces experienced by an impactor into dry granular media are purely related to gravity [6, 7]. Recent work by the PI [8] has shown that gravity plays an important role for slow impacts. Microgravity experiments also points towards the need of variable gravity impact experiments [9]. Performing granular impact experiments on the Moon can provide us with the necessary scalings of impact dynamics with **D** and **H**, which are difficult to arrange on parabolic flights. Such experiments would offer a unique opportunity to collect data on probe impact dynamics with entirely different gravitational forces acting on both impactor and the granular medium. Additionally, the near perfect vacuum on the Moon provides an ideal test bed as it also eliminates all particle-fluid interactions known to be important in impact dynamics [10].

Embedding - Lunar gravity impact experiments can complement experiments currently proposed for the ESA Soft Matter Dynamics experiments running on ISS, which has its mission to "Study of the dynamics in driven granular matter, dynamical slowing down and heterogeneities, influence of dissipation, and friction among particles." Additionally, sensing technology can be further developed within existing collaborations with ESA microgravity flights program. The PI has a strong expertise in running complementary numerical simulations

[8, 11] whose comparison with experimental data would further enhance the value of even a small number of lunar impact experiments. In short, a NASA-led set of experiments on granular material impact dynamics that encompasses numerical simulations as well as microgravity and Earth-based experiments can utilize the strength of the US-led progress in the field [1, 6, 11, 12] and make real progress. The core information gleaned from such experiments has major benefits for both fundamental understanding of planetary formation and asteroid composition dynamics as well as for earth-science. The PI has a very favorable position to be a productive member of such a collaboration. He has a long-standing collaboration with L. Kondic [1, 11] who was already involved in the ESA Soft Matter Dynamics experiment. He has existing collaborations (VSP program) with J. A. Dijksman [13, 14], a granular materials expert from the Netherlands who is currently coordinating a 14 PhD student-large EU H2020 funded hybrid experimental/computational granular dynamics program called Caliper (www.caliper-itn.org). This Caliper program puts the PI directly in touch with low gravity granular dynamics expert R. Stannarius [15], member of Caliper. Prof Sperl, the leader of the ESA Soft Matter Dynamics experiment [16, 17] has also expressed interest to collaborate with the PI and his group on granular experiments and has expressed willingness to test the Smarbles impact sensor platform on ESA-led parabolic microgravity flights.

Citizen Science – Impact experiments are also a unique opportunity to offer citizens from around the world a way to participate in basic science. While the complete dynamics of impacts are still beyond our current understanding, basic ingredients of impact dynamics touch upon simple physics concepts and can be thus be used to explain such concepts to students and/or enthuse new generations of students for science. If live data from lunar explorers performing impact experiments can be made accessible to citizens, these experiments would offer a unique opportunity to interactively reach out to a large number of people.

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