LOW-GRAVITY CENTRIFUGE FACILITIES FOR ASTEROID LANDER AND MATERIAL PROCESSING AND MANUFACTURING. E. Asphaug[1], J. Thangavelautham[2], S. Schwartz[1], [1]Lunar and Planetary Laboratory, University of Arizona, Tucson AZ, [2]Space and Terrestrial Robotics Laboratory (SpaceTREx), Aerospace and Mechanical Engineering, University of Arizona, Tucson AZ, {asphaug, jekan, srs}@arizona.edu

Introduction: The Deep Space Gateway has the potential to open new avenues for human exploration towards the Moon, asteroids and Mars. In the next 35 years, we aspire to be on our way to sending human and robotic explorers to perform orbital, surface and subsurface exploration. These explorers will pave the way towards cataloging the diverse surface environments, physical processes and structures of the planets and small bodies answering fundamental questions about the origins of the solar system, conditions to sustain life and prospects for resource utilization and off-world human settlement. Achieving this major exploration milestone remains technologically daunting and therefore we consider the DSG as an ideal proving ground for the requisite technologies. Conditions on some of these planets and small bodies are not well understood.

Challenges: One of the major challenges in recreating or even understanding these off-world conditions is the low surface gravity. We lack fundamental knowledge of surface material properties, especially the dangers that may prematurely end a mission. Our lack of understanding poses a major risk due to inherent uncertainties in the design and development of robotic and human vehicles to explore the far reaches of the solar-system. This leads to significant cost increases, schedule delays and lack of technical or political confidence in these missions. This is a major concern for small-body exploration, where the low gravity makes surface landing and mobility extremely challenging, as evidenced by JAXA's first Hayabusa mission and ESA's Philae lander aboard Rosetta [1–2].

Physical processes in these alien environments may be simulated using ever-realistic computer models, but these models are dependent on our current domain knowledge. Ultimately, these computer simulations, as well as analytical scaling relations (e.g., [3]), need to be validated against the real thing. The logistics and resources required to reach these far corners of the solar system make the process of simulation validation and trial-and-error learning a very slow and cumbersome process as a mission, from concept to launch, may take 5–10 years or longer.

On-Orbit Centrifuge Laboratory: Our work has identified the use of on-orbit centrifuge science laboratories (**Fig. 1**) as a key enabler towards low-cost, fast-track understanding and simulation of off-world environments for the dual purpose of planetary science and exploration engineering. We have developed AOSAT I (Asteroid Origins Satellite I) [4–7], a 3U CubeSat (**Fig. 2**) that is intended as a low-cost proof-of-concept on-orbit demonstrator to show the feasibility of a centrifuge science laboratory for planetary science and to simulate asteroid surface conditions. The concept of an on-orbit centrifuge is not new [8–10]. Our work identifies new use for these as laboratories and proving grounds to simulate off-world environments. We envision follow-on missions that include enlarged centrifuges with much larger internal volume to test instruments and major parts of a spacecraft under alien surface conditions.

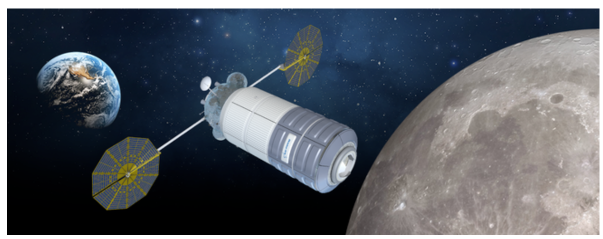

Fig. 1. An on-orbit centrifuge based on existing Space Station service vehicles (shown: Orbital ATK Cygnus) can be used as a laboratory and proving ground to simulate the range in gravitational conditions that exist on asteroids, comets and small moons. Planetary science instruments, scaled or full size spacecraft, and even astronauts can be trained or tested in these laboratories ahead of deep space missions.

Persistent Link to Off-World Environments: Using such laboratories it is possible to simulate alien environments (different gravity, atmospheric pressure, electrical conditions and so on) and test hypotheses for unknown or poorly understood planetary surface processes; this, in turn, may be used to validate computer models in order to develop advanced simulation proxies for science, exploration, mining, habitation, and hazardous asteroid deflection. By recreating alien surface environments we can test and validate robotic landing technology and human adaptation to these environments, and broaden our understanding and prove the feasibility of risky off-world surface exploration techniques before going to these locations [6].

These laboratories can be enlarged and transformed into miniature proving grounds for testing and demonstration of entire spacecraft and landing systems. They may be used to train and condition astronauts for efficient mobility and to perform both basic and complex tasks in the low-gravity environments of Moon and

Mars to sustain long-life expeditions. This may include evaluating self-sustaining farms and an artificial ecosystem to sustain the health and the well-being of human explorers. As a specific example, directly determining the effect of Martian gravity on plant-life will be critical in long term exploration and settlement of Mars and can be done in LEO (see **Fig. 3**).

Further, these facilities will require significantly less resources and budget to maintain, operating in LEO, compared to the voyages to deep space, and will hence serve an important tactical goal of preparing and maintainning readiness, even when missions are delayed or individual programs cancelled. Imagine being able to recreate Mars or lunar surface conditions to sand grain detail without having to go there. Imagine recreating a patch of the Moon and having astronauts train and adapt to lunar conditions from the end of the Apollo mission in 1972 till now. The technologies we propose facilitates our abilitiy to effectively accumulate and maintain knowledge to explore the diverse environments in our solar system.

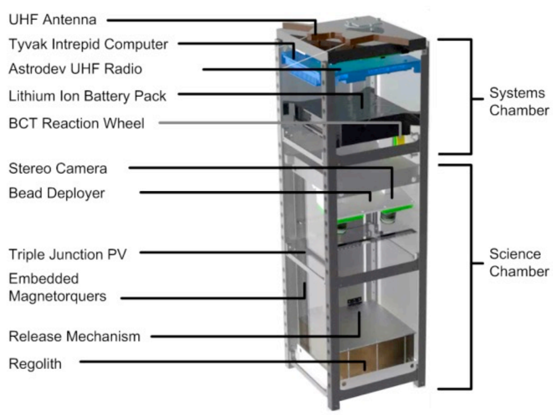

Fig. 2. Asteroid Origins Satellite 1 is proof-of-concept CubeSat demonstrator to be launched in the 2018-2019 timeframe. The mission will demonstrate an on-orbit centrifuge laboratory to simulate asteroid gravity conditions

By letting us have persistent access to simulated versions of these off-world environments, these laboratories will allow us to forecast and avoid surprises in-situ, and to increase confidence and support for such ambitious exploration endeavours. We also believe these facilities will be critical for resource prospecting and mining as they can be used to rapidly perform trial-and-error experiments, followed by refinement of the technology towards efficient surveying, extraction and processing of resources in-situ both for fuel, parts repair and settlement/infrastructure construction.

Conclusions: Centrifuge science laboratories, from CubeSat and larger scales, can be used to recreate the low-gravity off-world conditions of the Moon, Mars, asteroids and other small bodies in the solar system. The laboratories can provide a persistent link to better understand and perform hypothesis-testing of planetary surface processes. The power of hypothesis-testing of planetary science processes, being able to fully recreate them in controlled laboratory conditions in low-Earth orbit, and to prove or disprove hypotheses directly, will have major consequences for the field. Detailed numerical simulation environments can be developed and validated for end-to-end process testing. Furthermore, this technology can be applied to de-risk next generation spacecraft technology especially for landing, surface mobility and even for subsurface exploration with increased confidence and long term planning.

Estimated Resources:

- Mass: 1000 kg
- Power: 120 W
- Cost: $100 M
- Volume: 2 m^3
- Crew interaction: limited
- Preferred orbit: L2 (or any)
- Temperature control: -50 to +80°C

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