MILO APOPHIS PATHFINDER. James F. Bell, III[1], Ryan S. Park[2], James W. Rice, Jr.[3], Young-Jun Choi[4,5], Hong-Kyu Moon[4], Myung-Jin Kim[4], Minsup Jeong[4], Bongkon Moon[4], Travis Gabriel[6], David E. Thomas[7]

[1]Arizona State University, Tempe, Arizona 85281, Jim.Bell@asu.edu, [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, [3]Arizona State University, Tempe, Arizona 85281, [4]Korea Astronomy and Space Science Institute, Daejeon, Korea, [5]University of Science and Technology, Daejeon, Korea, [6]USGS, Flagstaff, AZ 86001, [7]The MILO Space Science Institute, Arizona State University, Tempe, Arizona 85281.

Introduction: The near-earth object (99942) Apophis will have an extremely close approach to Earth, passing within 10% of the distance between the Earth and the Moon, and well within the planet's geosynchronous satellite ring. This extremely close pass of such a relatively large object represents a unique opportunity to study a potentially hazardous object. Flyby data would provide new scientific information on asteroids like (99942) Apophis, a so-called "S type" asteroid, similar to the LL Chondrite meteorite class according to its visible to near-infrared spectrum (similar to more than 80% of the other known near-Earth asteroids). Data would enhance advance planning for future missions to (99942) Apophis and provide additional data needed to formulate future Planetary Defense strategies.

Due to the immediate relevance to crafting planetary defense strategies and the abundant scientific return this opportunity provides, several space agencies and space mission developers have already begun to discuss mission architectures that might capture high profile scientific data. The MILO Institute has designed a dedicated mission that would focus specifically on performing the first- ever close flyby of asteroid (99942) Apophis and feed forward information to other missions. The MILO Apophis Pathfinder mission would conduct a flyby precursor investigation of the asteroid several years in advance of the Apophis 2029 Earth flyby, using a pair of small spacecraft to provide initial reconnaissance data, to inform and influence planning for additional missions to (99942) Apophis in 2029 and beyond. Science objectives include more precise estimates of mass and density, shape, geology, composition, and orbit parameters – while helping to inform planetary defense strategies. The key information obtained from this mission will also be of great help in planning the scientific research goals and operation scenarios for the RMA (Rendezvous Mission to Apophis) mission planned by KASI [1].

Collaborative Mission Structure: The MILO Space Science Institute at Arizona State University was formed to provide affordable access to space science missions. The model is built on the hypothesis that compelling, science-driven deep space robotic missions can be led, organized, and conducted by a consortium of U.S. and international organizations. Collaborative efforts between partner organizations in space is an optimal arrangement for the scientific community, maximizing knowledge sharing and research opportunity while mitigating risks. Partnerships and teaming allow for conjunction of the best aspects of all participants, such that the capabilities of an effective team may be greater than its sum of its individual members, with improved opportunity for mission success and meaningful scientific contributions. Shared missions between purposeful spacefaring organizations have a long history of accomplishment – and are notable in their potential for pushing boundaries or high-impact research.

Mass Estimation: The mass of a NEO is one of the most important parameters from the perspective of planetary defense and planetary science. However, the mass of most asteroids in the solar system is unknown. Atchison et al. [2] proposed a concept called OpGrav that uses a probe-based measurement method, as successfully demonstrated by the Small Body In-Situ Multi-Probe Mass Estimation Experiment project [3]. In a recent paper Christensen et al. [4], examined how the OpGrav concept may be improved and from a flyby by deploying a series of probes ejected from the host spacecraft which can provide the following benefits:

1) Such probes can be made to approach the asteroid at much closer distances without endangering the spacecraft, thus providing increased deflection.

2) The relatively short distances between the probes and the spacecraft will allow for more precise observations compared to the Earth based tracking of the spacecraft.

3) By having the probes approach the asteroid at different distances and/or from different directions, the differential deflection of their trajectories can be used to pinpoint the mass of the asteroid, even though its position is not well determined.

4) If the probes are constructed with adequate uniformity, it can reasonably be assumed that any external disturbances will affect them equally, thus allowing for such disturbances to be decoupled from the gravity of the asteroid. Solar radiation pressure will, for example, result in an acceleration term that is approximately equal for all probes, whereas asteroid gravity will affect them differently. By looking at the difference between the probes, solar radiation pressure

will thus disappear while gravity is retained. The probes can, in principle, be as simple as small inert spheres coated in a highly reflective material that allows them to be imaged from large distances for angles-only camera measurements.

A hypothetical mission to a main-belt asteroid was used as a reference, and an extensive covariance analysis performed to determine the recoverable mass accuracy under various conditions. The result showed that, under realistic assumptions, the mass of a Bennu-like asteroid can be recovered with a 1σ accuracy better than 20% from optical tracking. In case radio transceivers are considered, the recovered asteroid mass accuracy reduces to better than 5%.

Miniaturization: Multiple SmallSats are planned for unique, independent missions to both the Moon and asteroid belt within the next five years to offer meaningful capabilities like prospecting, multispectral imaging, and advanced technology demonstrations. In 2022 Artemis I will co- manifest ten CubeSats from international, industry, and academic partners to address a wide range of science goals, and the dual Janus probes, with mass less than 36 kg each, will set off for science missions at two binary asteroids. The Italian-made LICIACube is currently travelling with DART as a valuable mission augmenter, and ESA will follow the mission in 2024 with host- spacecraft Hera, which will provide additional asteroid science through its secondary CubeSat payloads Juventus and Milani. In 2025, the Lunar Trailblazer SmallSat will begin its mission to detect and map water on the Lunar surface.

SmallSats are working together to produce new science, or acting as critical mission augmenters for larger spacecraft. Multiple probes operating together are able to offer data which could not have been measured by one spacecraft alone, while iterative missions, like DART and Hera to the asteroid (65803) Didymos, offer critical phased approaches in which follow-on missions are empowered act on the findings, impacts, or experiments of their predecessors.

Miniaturization of electronics and their enhanced capabilities have reduced their physical profiles within satellites, while retaining radiation resistance, improving antenna efficacy, pre-processing data before transmission, and lowering power draw. Vastly upgraded solar array efficiencies and battery technologies have also afforded spacecraft improved access to electricity with reduced mass or volume constraints. Together, these fundamental augmentations reduce requisite spacecraft size overall, in turn reducing the requirements for propulsion systems – which have themselves been improved by new fuels, additive engine manufacturing, and higher efficiencies over time.

Summary: The MILO Institute has designed a collaborative mission, deploying two small satellites similar to the Janus mission, to estimate the mass of (99942) Apophis using the OpGrav concept with radio transceivers to capture time of flight and measure the distances between the probes. Probes would be ejected from the host spacecraft during a flyby. The motion of the probes would be perturbed by the asteroid's mass during close approach, which could be tracked with an imager on the host spacecraft and measured with high precision. Change in relative separation between probes is directly proportional to asteroid mass. The addition of radio transceivers inside the probes would further enhance the mass-recovery performance.

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