APOPHIS 2029 PLANETARY DEFENSE MISSION OPTIONS. A. F. Cheng¹, R. T. Daly¹, O. S. Barnouin¹, J. B. Plescia¹, R. P. Binzel², D. C. Richardson³, J. V. DeMartini³, N. C. Schmerr³, J. M. Sunshine³, C. M. Ernst¹, B. W. Denevi¹, and J. T. S. Cahill¹. ¹Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA (andy.cheng@jhuapl.edu), ²MIT, Cambridge, MA, ³University of Maryland, College Park, MD..

Apophis 2029: The Potentially Hazardous Asteroid (PHA) 99942 Apophis will make an extremely close approach to Earth on 13 April 2029, within ~ 0.1 lunar distance or ~ 37000 km. Through 2200, no other PHA will approach as close to Earth. Apophis is an elongated, prolate Sq-type Near Earth Asteroid [1, 2, 3] with a mean diameter of 340 m as measured by radar [2]. Approaches to Earth of any object as large as Apophis, and as close as Apophis in 2029, occur about every thousand years.

Apophis was discovered in 2004 and was recognized as a PHA with impact probability on the Earth initially estimated at 2.7% in April 2029. However additional optical observations from 2004 and planetary radar observations in 2005 and 2006 ruled out the possibility of an impact in 2029 [4, 2].

Instead Apophis will make an exceptionally close approach to Earth in April 2029, so close that tidal stresses and torques may cause resurfacing or reshaping of the body and changes in its spin state. The close approach to Earth is a rare opportunity to observe a natural experiment that will probe the structural and physical properties of the surface and interior of an asteroid for the first time. [5]

The close approach also hugely amplifies the uncertainties of the Apophis heliocentric orbit propagation after the April 2029 Earth swingby. Apophis, like a number of other well-known NEAs, e.g. 1950DA, Bennu, and 2009 FD, may pass through one of many keyholes in its 2029 Earth swingby, which would put Apophis onto an Earth-resonant impact trajectory. However, Apophis is

unlike these other very hazardous asteroids, in that the possible future Earth impacts lie only decades away, and not many centuries. The earliest keyhole-associated Apophis impact on Earth occurs in April 2060, and Apophis impacts are not possible before then. The highest-probability keyhole leads to Earth impact in April 2068 [1]. It is an important planetary defense objective specifically to better quantify and determine the future Earth impact risk from Apophis, where future includes possible impacts within 40 years after 2029.

A dominant contributor to the uncertainty of the heliocentric orbit propagation is the Yarkovsky drift, the non-gravitational acceleration from asymmetric thermal radiation which causes a slow drift in the heliocentric semi-major axis. The Yarkovsky effect is calculated to account for a ~ 300 km shift in the 2029 b-plane position (the plane normal to the incoming asymptote of the Apophis trajectory relative to the Earth that contains the geocenter, compared to a purely gravitational trajectory solution [1]. This modeled Yarkovsky effect is the dominant factor determining that Earth impact is not possible before 2060 and that the 2068 keyhole has the highest probability.

Hence quantifying the future impact hazard from Apophis requires not just precise navigation for orbit determination but also determination of the Yarkovsky effect, which requires shape, thermal inertia distribution over the surface, and spin state. All of these would be best determined by a mission to Apophis in 2029. Apophis would be an important object to study solely for its interesting and unusual spin state, tumbling in

Short Axis Mode [6] with strongest observed periodicity of 30.56 hours (precession and rotation periods of 27.3 and 263 hours, respectively). What's more, the 2029 Earth encounter may change the non-principal axis rotation state, because of tidal torques and/or tidally-induced changes in mass distribution or shape [6, 7, 8].

The Apophis 2029 apparition provides a rare opportunity to visit Apophis with a spacecraft and to make vital measurements for planetary defense. The tidal stresses induced in the 2029 Earth encounter, which may lead to resurfacing or mass motions, also provides an opportunity to address fundamental questions about interior structure and to measure surface physical properties like strength and porosity that are fundamental to understanding collisional evolution and regolith formation. These physical properties and internal structure measurements are also critically important to future asteroid mitigations, as they determine the physical effects that would be necessary to accomplish a deflection or a disruption of a future hazardous asteroid. They strongly affect both the amount of momentum transferred to a target by a kinetic impact and the threshold for catastrophic disruption.

Strength in particular is highly uncertain and has been measured only once at a comet and once at an asteroid. The Rosetta Philae lander at 67P/C-G found at its touchdown a very weak surface layer (strength of about 1 kPa) but also a shallow subsurface indurated layer that was too strong to drill through, implying a strength at least 2 MPa [9]. The Hayabusa 2 SCI experiment performed an artificial impact on Ryugu, which unexpectedly formed a much-larger-than-expected crater, consistent with gravity-controlled cratering and surface strength of at most on the order of 1 Pa [10], a thousand times less than the weak surface layer of the comet.

Strength measurements in the regolith are fundamental to understanding regolith formation and collisional evolution of small bodies, for two reasons. The first reason is to understand the threshold for catastrophic disruption, meaning the specific impact energy per unit target mass to cause catastrophic disruption, which is fundamental to understanding the size distribution of the collisionally evolved small body population and determining which bodies are actually primordial as opposed to collisional fragments of much larger parent bodies. The catastrophic disruption threshold is much affected by internal structure, depending on whether there are large, consolidated components (how many? how large?) and how much friction and cohesion of these components contribute to maintaining body shape versus gravity.

The second reason motivating strength measurements of surface materials is key to understanding regolith formation and evolution on small bodies, because it affects the proportion of collisional impact ejecta which can fall back to the surface of the body. At high surface strength, ejecta are produced predominately above the escape velocity for an NEA, and little or no ejecta fall back to the surface. However, for surface strengths as low as those found at comet 67P/C-G (about 1 kPa) or especially Ryugu (about 1 Pa), a substantial fraction of the ejecta mass can return to the surface forming regolith even at the small size and low gravity of NEAs the size of Apophis. Alternatively, regolith may be formed not by impacts on the body in its current size and shape as an NEA, but formed earlier on its parent body or in the catastrophic disruption event that produced fragments that re-accumulated gravitationally to form the body. The boulder distribution on Itokawa is inconsistent with having formed on present-day Itokawa [11], which is similar in size to Apophis, so Itokawa's regolith

formed on a parent body or in the catastrophic disruption.

Apophis in its 2029 apparition will come to about $6 R_E$ from Earth's center, which is well outside the classical Roche limit (for density 2.4 g/cm^3 , the Roche limit is at $3.2 R_E$). Hence tidal disruption or significant reshaping of Apophis are not expected from the 2029 flyby of Earth, but small-scale surface mass motions and/or boulder displacements may be triggered [5, 12]. Expected changes in the gravitational slope angle during close encounter are at most on the order of $\sim 1^\circ$ [5], which could possibly trigger localized mass motions in places where the slope is already very steep. Predicted changes in the lengths of the principal axes of the Apophis shape model are less than $\sim 1 \text{ mm}$ [12]. However, substantial changes in the spin state of Apophis (by several hours, of either sign) may be induced by tidal stress during the Earth flyby [7, 8, 12].

Tidally-induced resurfacing of NEAs during Earth close approaches is of particular importance because this process may explain the apparently fresh and unweathered surfaces of Q and related type NEAs [13, 14]. Dynamical studies of these objects found that those bodies had a greater tendency to come close to the Earth, within the Earth–Moon distance, than bodies of other classes in the past 500 kyr. A mission to Apophis in 2029 provides a unique opportunity to test this idea and to characterize the resurfacing that may occur during the exceptionally close 2029 encounter of an object as large as Apophis.

Apophis 2029 Planetary Defense Mission (PDM): To be able to observe the changes that may be induced by the close approach to Earth, the Apophis 2029 PDM must rendezvous with Apophis some months in advance of the close approach on 13 April 2029 and then remain in rendezvous with Apophis for several months afterwards. Small

body rendezvous does not necessarily imply continuous orbiting of the target, but can include partial orbits, multiple slow flybys, and landed experiments, as was done for example on Hayabusa and as planned for Hera. Chemical mission opportunities have been identified that could launch in late 2027 and arrive at Apophis in late 2028, with a medium launch vehicle and with total post-launch $\Delta v < 1800 \text{ m/s}$.

Mission goals and measurement objectives are summarized in Table 1. The objectives fall into three main goal areas: impact hazard risk assessment for the long-term future after 2029; use of the 2029 Earth close encounter to make determinations of physical properties that would greatly reduce risk for any future mitigation; determinations of asteroid interior structure. Apophis 2029 PDM will map the entire surface before and after the Earth flyby, and it will emplace seismometers and monitor seismic activity induced by the Earth flyby [12] as well as activity from micrometeorite impacts and thermal fracturing. It will conduct an active seismic experiment and perform radar tomography to characterize internal structure, and it will observe and measure changes in the Apophis spin state from the Earth flyby.

The mission concept uses a rendezvous spacecraft with one or more CubeSats that may be close-in orbiting or landed experiment packages. Mission implementation options include accommodation of particular experiments on the rendezvous spacecraft or on CubeSats. The rendezvous spacecraft will carry a narrow-angle, high resolution visible imager (VIS) for optical navigation and for performing the high-resolution imaging needed to determine shape and size, to observe any changes in Apophis from the Earth flyby, and also to measure the spin state before and after the flyby. This camera should have 10 cm resolution from 20 km range. The rendezvous spacecraft maintains a home position, where it is tracked by and

communicates with Earth. Many of the other instruments can be carried on 6U CubeSats that are tracked by and communicate with the rendezvous spacecraft. In particular, visible and near infrared (VNIR) spectral imaging, thermal infrared spectral imaging (TIR), a gravimetry experiment, a Low-Frequency (LF) ground penetrating radar, and seismometers can be on CubeSats. The LF radar experiment may be a sounder experiment to probe interior structure, or it may be a bi-static experiment, between a landed package on a CubeSat and the rendezvous spacecraft, performing tomography of the interior.

Table 1. Apophis 2029 Mission Objectives

Mission Goals	Measurement objectives	Techniques
Provide long term Earth impact risk assessments	Orbit determination and propagation after 2029	Radiometric tracking
	Yarkovsky drift determination	Radiometric tracking, TIR imaging
Determine physical properties relevant to asteroid hazard mitigation and to asteroid collisional evolution and regolith formation	Observe and measure changes in surface features and shape/morphology	High-resolution VIS imaging, VNIR and TIR spectral imaging
	Determine geotechnical properties, including strength and porosity	Seismometry, active impactor experiment, RF gravity or gravimetry
	Observe and measure changes in Apophis spin state	High-resolution VIS imaging
Determine interior structure	Characterize subsurface interfaces, layers, blocks, or voids	LF radar, seismometry, RF gravity or gravimetry
	Observe any changes from flyby or from active impactor experiment	LF radar, seismometry, RF gravity or gravimetry

One or more of these experiments (e.g., thermal imager, radar sounder, or active impactor) may alternatively be accommodated on the rendezvous spacecraft. The active impactor experiment would have two objectives: to create a small crater or craters and to provide artificial seismic stimuli, and can be accommodated on the rendezvous spacecraft. The active impactor provides seismic signals to probe the interior structure and physical properties, and it supplies momentum inputs far too small to cause any measureable deflection of Apophis. The gravity field determinations may be from a dedicated gravimeter in close orbit or landed on Apophis, and/or from Radio-Frequency (RF) tracking of CubeSats from the rendezvous spacecraft. An altimeter on the rendezvous spacecraft may further contribute to size, shape and gravity determinations.

In conclusion, the 2029 Apophis Earth flyby is a unique opportunity to obtain vital information for planetary defense by studying Apophis, determining its internal structure, and observing possible changes due to tidal effects from the Earth flyby.

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