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APOPHIS 2029: PLANETARY DEFENSE OPPORTUNITY OF THE DECADE

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ABSTRACT

The 350-meter asteroid (99942) Apophis, an object 5-times larger and 100-times more massive than the Tunguska impactor, will safely miss the Earth on Friday April 13, 2029. However its close flyby distance at an altitude of 31,000 km (closer than geosynchronous satellites) provides a once-per-thousand year natural experiment as a learning opportunity for science and planetary defense. A call is made for detailed studies of what physical effects, if any, may be induced on Apophis by Earth's tidal forces. By corollary, mission concept studies are needed to explore how measurements of any physical effects of this "natural experiment" may be used to deduce the internal and structural properties of potentially hazardous asteroids. The 2029 encounter opportunity makes Apophis the "poster child for planetary defense" transitioning the field to a new era from space situational *awareness* to space situational *understanding*.

1. Introduction

Nature is providing a once-per-thousand year opportunity for Planetary Defense with the 2029 April 13 near-miss passage within 6 Earth-radii of the 350-meter asteroid Apophis. On that date, Apophis' transit across the evening sky will be visible to the naked eye for approximately 2 billion people residing in Africa and western Europe. This paper seeks to motivate ongoing investigations of the learning opportunities presented by the Apophis flyby. Three aspects make the Apophis 2029 encounter particularly unique as an outstanding opportunity for advancing our knowledge of potentially hazardous asteroids: 1) the size of the object and the rarity of such a large object passing within one-tenth the lunar distance, 2) the close encounter distance is at or near the limit for which Earth tidal forces might induce measureable stresses or vibrations within the interior to the object - possibly producing observable surface morphology alterations, and 3) having more than a decade of advance awareness to evaluate, plan, and execute mission opportunities.

Interiors of asteroids remain *terra incognita,* just as the interior of Mars has remained unknown for millenia up to the time of the current *InSight Mars* mission. Thus, the fundamental question: "What is the internal structure of a potentially hazardous asteroid?" is of interest both for science and for planetary defense. Here we argue that the objectives for science and planetary defense are all one in the same. As an axiom, we propose: Knowledge is the first line of planetary defense. ("Know thy enemy.") From the observed outcome of the 2029 encounter it may be possible to determine whether Apophis is a solid monolithic body or loosely held conglomerate "rubble pile." For the latter, the scale of internal fracturing could range from Apophis being a "gravel pile" comprised of countless fragments to being a bi- or multi-lobate structure of just a few large blocks. These vastly different physical constructions have a correspondingly huge range of intrinsic strengths; dramatically illustrating unconstrained challenges to be faced by any future eventuality of actual planetary defense mitigation planning. Having specific knowledge of the detailed internal structure for one potentially hazardous asteroid (rather than zero) could prove invaluable to the security of future civilization.

2. Physical State and Physical Effects on Apophis

The largest scale consequence imposed by the Earth during the 2029 encounter will be to alter the orbit of Apophis, resulting in an increase in its orbital period [1]. Here we focus on the physical response of the body that is Apophis itself. Apart from the minimum Earth miss distance, the most important factors affecting the physical response of Apophis during the encounter are its shape, internal structure, rotation rate, and physical orientation at closest approach. The basic composition of Apophis, including the density of its constituent material, appears to be well established based on telescopic reconnaissance of its surface spectral refelectance [2,3]. Apophis appears to have the make-up of the most commonly falling meteorites, the stony ordinary chondrites. (Apophis appears to fall in the specific class of LL chondrites.) Because the stony meteorite category of Apophis is highly typical of the majority (about 80 percent) of potentially hazardous asteroids, knowledge gained on Apophis itself will be most broadly applicable to the entire hazardous asteroid population.

Based on analysis of rotational lightcurve variations [4], Apophis is found to be in a "tumbling state" with a precession period of 27.4 hours and a slow rotation period of around 260 hours. Detailed radar studies [5] confirm the tumbling state and the corresonding long periods. Most likely this complex rotation state is the outcome of a previous Earth encounter that was substantially closer than occurring in 2029. (The timescale for damping such tumbling motions can be of order 10^5 to 10^6 years making the timing of a previous encounter highly uncertain.) The extent to which such a previous close encounter re-shaped Apophis, perhaps allowing it to relax into a highly stable minimum energy internal structure, is presently unknown. Such a stable internal state would mitigate any observable consequences of the 2029 flyby.

The slow rotation and precession rates of Apophis may also be key factors that mitigate against a strong physical response, e.g. seismic shaking, being induced by the 2029 encounter. Current predictions are varied for the occurence and measureability of any response [see for example 6,7,8], motivated by the apparent resurfacing (as deduced by surface spectral variations) that occurs on near-Earth asteroids as a consequence of planetary encounters. [9,10]. The somewhat large 2:1 axis ratio for the elongated shape of Apophis [5] may bolster the chance for significant physical response if the long axis of Apophis happens to be oriented toward Earth at the time of closest approach (thereby allowing tidal forces to exert a maximum torque). A radar observation opportunity in 2021 may refine the spin state and orientation of Apophis sufficiently well to define its axis orientation during the 2029 encounter and thereby improve the fidelity of predictions for the observable consequences.

With the boundary conditions of shape, rotation state, and encounter orientation determined, the outstanding variable for any measureable physical effect is the internal structure of Apophis - the holy grail for informing both science and planetary defense. By instrumenting the surface of Apophis, or devising standoff measurement techniques, mapping the seismic wave propagation provides the first ever opportunity to map in detail the internal structure of a potentially hazardous asteroid. Just like *InSight Mars* is opening an entirely new realm of investigation of planetary geophysics, seismic measurements of Apophis will open an entirely new field of asteroid geophysics. Thus the once-per-thousand-year encounter of an asteroid this large passing this close to Earth holds the promise of breakthroughs across many disciplines to the benefit of science and planetary defense with the most important consequence being advancing our understanding toward securing our asteroid future.

3. Apophis Mission Architectures

Concepts for Apophis mission architectures are in their infancy and this section seeks to simply delineate a range of possibilities. Apophis' sub-Earth point at closest approach over the mid-Atlantic ocean is optimal for Arecibo radar measurements [5] and any flight mission must justify its measurement deliverables relative to what can be achieved by groundbased assets. Most studies to date [11, 12] have considered rendezvous spacecraft. As an example, the MIT Project Apophis student-led study [12], modeled after the MIT Project Icarus study [13] exactly fifty years earlier, identified a 2026 launch opportunity using solar-electric propulsion arriving at Apophis in March 2028. The early arrival allows detailed characterization of the asteroid before encounter, forming the basis for comparison of physical changes induced by the encounter. Radio Reflective Tomography is employed for mapping the interior structure before and after encounter. As an extended mission, the spacecraft tracks with Apophis for several additional years acting as a beacon to measure the evolving orbital changes due to the Yarkovsky effect.

Apophis' incoming arrival into the vicinity of Earth offers the opportunity for small satellites (for example cubesats) to be residing in Earth orbit. A swarm of cubesats might be envisioned as being optimally placed to capture images and other measurement data as Apophis whizzes through the crowd of sensors, effectively a low cost "paparazzi" approach to mission architecture. However, such Earth-vicinity spacecraft are faced with the challenge of the high 7.4 km/sec relative velocity of Apophis' trajectory through the Earth-Moon system.

At the most fundamental level for any Apophis mission concept is whether or not any instrumentation is placed in contact with the asteroid surface. The MIT Project Apophis study dubbed two surface options as "smart marbles" and "dumb marbles." Landed packages that are "smart" contain sensors that report measurements back to the mother ship and perhaps communicate with another. For the case of "dumb marbles" these are simply low cost (and hence can be numerous) objects of known mass and cohesion characteristics that may be spread broadly across the surface. Standoff imaging of their motions, if any, are used to deduce the extent of surface vibrations. An intriguing option for measuring seismic signals without physical contact is the use of laser vibrometry [14].

A mission concept that does include landed instrumentation or laser vibrometry might also consider an active experiment (explosive charge or kinetic impactor) that is executed some time after the Earth encounter. By executing the controlled experiment, any measured activity induced by the encounter becomes carefully calibrated. Perhaps even more importantly, the investment of seismic instrumentation is more assuredly guaranteed a measureable signal, considering any tidally-induced consequences remain a significant unknown. International policy considerations may come in to play for any physical interaction with Apophis that may be construed as having any measureable effect on its future orbit. A criterion for the maximum consequence for any interaction may be for that interaction not to exceed the offset caused by the Yarkovsky effect as measured over one century.

4. Conclusion

The path ahead for spacefaring nations responding to the 2029 Apophis close-approach opportunity is still unfolding. At the time of this writing, formal recommendations are mounting for considering one or more missions. NASA's Small Bodies Assessment Group (SBAG) issued a finding in January 2019 encouraging *NASA and the small bodies community to determine the science and planetary defense goals for the 2029 Earth flyby of (99942) Apophis, and to evaluate the opportunities, both in space and on the ground, that the flyby affords.* Similarly, a resolution passed by the 2019 International Academy of Astronautics Planetary Defense Conference acknowledged that *the occurrence of such a large asteroid flyby is a once-per-thousand year natural event that will provide a unique opportunity for advancing small body knowledge for both science and planetary defense.* Thus, all signs point to widespread recognition of the Apophis 2029 event as the Planetary Defense Opportunity of the Decade.

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