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Introduction: In order to maximize the time available for planning and carrying out actions, it would be useful to launch an intercept mission as soon as possible after initial detection of potentially hazardous objects (PHOs) approaching Earth. However, keeping a fueled rocket with a conventional probe on standby would be logistically difficult and prohibitively expensive. In this paper, we propose using laser-driven light-sail probes to implement quick-reaction missions to intercept PHOs approaching Earth, with an initial test of this capability using the upcoming close approach of Asteroid 99942 Apophis.

Apophis is a near-Earth asteroid more than 1000 feet (over 300 meters) in size that will harmlessly pass close to Earth on April 13, 2029 [1]. A 2029 laser sail mission to intercept Apophis would serve as an excellent precursor exercise for intercepting PHOs and other objects of interest.

We want to intercept such PHOs well before their closest approach in order to acquire precise trajectory data, thus accurately determining the probability of impacting Earth, and to acquire images and other data to determine its makeup – whether iron, stony, chondrite, or ice [2] – and accurately plan potential courses of action. Even a gram-class sail probe could perform these functions.

The *Breakthrough Starshot* project [3] seeks to launch interstellar probes to Alpha Centauri. To keep costs reasonable, it proposes using small, extremely light-weight light-sail craft accelerated by a very-high power (gigawatt class) array of lasers. In this paper we propose developing a precursor mission to *Breakthrough Starshot* which would use available, if bleeding-edge, state-of-the-art technology to launch and accelerate sail-craft with lasers to quickly intercept Apophis during its approach to Earth, returning imagery and trajectory data and planting an RF beacon. This effort would demonstrate that laser-driven light-sail craft are indeed feasible, capable of fast-reaction missions, and can be successfully used to intercept an Earth-approaching asteroid. Once demonstrated, such sail-craft could be used for other missions as well, such as intercepting passing interstellar objects (ISOs) passing through the Solar System, e.g. 'Oumuamua [4].

Light-Sail Probes: Conventional light-sail craft utilize either a towed-payload design, where the payload hangs from shrouds behind the sail, like a parachutist hanging from a parachute, or an extended-boom design, where the payload sits in the middle of the sail, fastened to booms extending outward. Both of these approaches present significant issues for this effort, particularly that the payload will be subjected to the full intensity of the drive beam. We propose a solid-sail approach in which the sail is a solid body, albeit made from ultra-light materials, with the entire rear surface being the reflective sail element and the electronics mounted on the forward layer.

In such a sail-craft, the body would be constructed of a 3-D printed ultra-light/ultra-rigid fractal lattice metamaterial [5] of graphene and/or nickel. By prudently choosing the sizes of the various elements, materials rigidity, thermal conductance, and density may be tailored to the specific application. Lattices with densities less than 5 mg cm-3 have been achieved.

For the proposed mission, the probe takes the form of a shallow conical disk, 450 mm diameter and approximately 5 mm thick in the center, with a taper of approximately 2 degrees so that the edges are approximately 2 mm thick. The diameter allows the probe, along with an ejection mechanism, to fit into a standard Black Brant sounding rocket payload shroud for launch.

Guidance, control, communications, and sensor electronics are located on the forward side, bonded directly to the probe body. Sensors could include visible and infra-red imagers, spectrometers, and magnetometers. It should also be feasible to include a radar or optical transponder light-weight enough to survive – when cushioned by the probe's body material – an impact with Apophis.

The reflective side, which faces the drive laser, is coated with an ultra-reflective dielectric metamaterial optimized for the chosen laser wavelength [6]. This construction provides both the ultra-high reflectance needed for the probe to survive the intensity of the drive beam and a self-centering mechanism which will inherently center the sail in the drive beam [7]. The conical shape also stabilizes the craft during a possible atmospheric reentry.

Sail-Craft Drive Laser: Initial calculations show that using a drive laser at a wavelength of 1064 nm, which readily penetrates the atmosphere and is currently available with industrial fiber lasers, and a total drive beam intensity of 17 megawatt (MW), the probe as described can be driven to an apogee at 30,000 km, which would intercept Apophis. The thrust is directly against Earth's gravity; for this mission the probe would not be sent into an Earth orbit, although we will examine the feasibility of "pumping" a larger sail, deployed into low-Earth orbit, with the laser. A 2m aperture launch telescope provides an Airy disk the size of the probe at 1300 km, giving the practical limit of full laser thrust. The laser can still provide thrust past this point, but an increasing proportion of the beam, and thus thrust, will be pass by the sides of the probe.

Commercial industrial lasers are available with powers up to 1 MW. Multiple laser outputs may be combined using one of several techniques, the practical limitations of which will need to be established, and it may be necessary to use multiple telescopes in parallel to achieve the necessary launch power.

Apophis Mission: Apophis will pass approximately 30,000 km from Earth, traveling approximately 7400 m/s at closest approach, taking about 12 hours to cross the Moon's orbit.

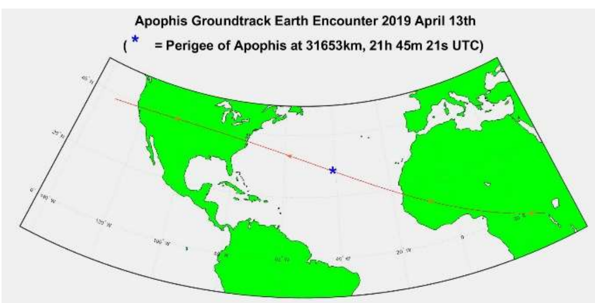

Figure 1 - Apophis trajectory during encounter. Ground track is from right to left and will proceed over possible launch sites in Virginia 42 minutes after perigee, and sites in Colorado and the Western US during the next 40 minutes

For this mission, two sail-craft would be launched on a Black Brant sounding rocket; one to be released at 75 km altitude – the minimum altitude at which the laser could still overcome atmospheric drag, the other at the rocket's maximum altitude of 1500 km. The laser would then thrust each probe in succession to 30,000 km apogee, timed to bracket the asteroid's pass so that one probe encounters it while falling back to Earth, the other while ascending. Both probes would acquire images and data from Apophis during their pass. One probe would be timed to impact Apophis so that the second probe could acquire data on the resulting debris plume. The impacting probe could also carry a hardened and cushioned transponder to enable future tracking of the asteroid.

One exciting possibility, dependent on further engineering analysis, is that the second probe could actually fly through the plume generated by the impact of the first and acquire samples of surface material in a manner similar to how NASA captured samples of Comet Wild 2 with the Stardust mission[8]. The probes are light enough to decelerate in Earth's thermosphere to relatively slow speeds and then fall slowly to the Earth's surface for retrieval.

The sounding rocket mission would test a rapid deployment mechanism appropriate for a fast mission to a newly discovered PHO. The same laser system may also be used to loft a larger sail from medium Earth orbit (or a lunar transfer orbit) into an Apophis rendezvous trajectory for science observations.

Conclusions: Laser-driven sail-craft launched by sounding rockets offer a relatively inexpensive, way to launch quick-reaction fly-by missions to PHOs and near-Earth asteroids. With some enlargement of the drive laser and the probe, low-cost missions to the Kuiper Belt, the Oort Cloud, and even passing free-flying interstellar visitors could be mounted.

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