PHACE: Potentially Hazardous Asteroid CubeSat Exploration Mission

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Introduction: Potentially Hazardous Asteroids (PHAs) are a group of specific near-Earth objects (NEOs) with absolute magnitudes H ≤ 22 (approximately corresponding to diameter ≥ 140 m by assuming the albedo of 0.14 [1]) and the minimum orbit intersection distance (MOID) ≤ 0.05 au of Earth's orbit. Those characteristics of PHAs make them very likely to destroy a region on Earth in case of an impact. So far there are about 2000 PHAs identified, yet most of them remain uninvestigated. In-situ observation and measurement carried out by space missions thus becomes essential for defining successful "mitigation strategies" from the perspective of planetary science and defense. Seeing that CubeSats are proven as a cheap and versatile solution for NEO probes with developing mission proposals and concepts [2 - 4], here we propose a 6U CubeSat mission PHACE (Potentially Hazardous Asteroid CubeSat Exploration) to investigate the asteroid 99942 Apophis. It was first discovered and identified as a NEO in 2004, but soon caused a brief period of concern because the probability of Apophis hitting Earth was estimated 2.7% in the year 2029. Fortunately, the striking probability reduced with the increasing and improved ground-based observations of the asteroid, and the concern of 2029 impact was eliminated during its 2013 pass. On April 13th (Friday) 2029, Apophis will come to a distance of around 38422 km (~0.000257 au), which is ten times closer than the moon and almost the altitude of geosynchronous satellites. Such a close encounter of an asteroid will open a window of possible rendezvous with spacecrafts only by a very low ΔV (velocity impulse), which is considered in particular beneficial to CubeSats as their propulsion system is very limited.

Mission objective: PHACE aims to rendezvous with Apophis during 2029 and perform physical surveys with a high-resolution camera and a NIR spectrometer on board. By the combination of the instruments, a series of measurements can then be taken: positioning, shape, rotation, albedo, thermal inertia, surface temperature, surface morphology, and regolith properties. The data can serve as a comparison to the results of ground-based observations or thermal-physical models.

System definition: Our CubeSat is primarily based on the use of Commercial Off-the-Shelf (COTS) products as they stand for mature techniques (i.e., high TRL) and thus allow a more reliable design. The material added to the bus structure can provide adequate shielding for these devices. All components will be assembled on the Pumpkin 6U Supernova structure (TRL 9) of 1.1 kg. Table 1 lists the general information of all PHACE subsystems. The peak power consumption of science mode will be about 62.14W in total with 30% margin. Total cost of the mission is roughly estimated $3 - 4 million, which is ~1% of the budget of a traditional space mission targeting asteroids (e.g., Hayabusa 2).

Table 1. Manufacturer (Mfr.) with Type Specification (TS) and Technology Readiness Level (TRL) of PHACE subsystem components. [*note: JPL's Iris transponder is not COTS but we desire a multi-band transceiver as competent as Iris.]

Subsystem	Mfr. & TS	TRL
Camera	MSSS ECAM-C50	9
Spectrometer	Thoth Argus 1000	9
OBDH	ISIS iOBC	9
EPS	Nanoavionics EPS 2S4P	9
UHF/ S/ X Antenna	(UHF) Nanoavionics UHF 4 monopole	9
	(S) IQ Spacecom patch *6	
	(X) patch 4x4	
S/X/UHF Transceiver	JPL Iris V2.1*	9
ADCS	Blue Canyon XACT-50	9
Thruster	IFM nano thruster SE	9
TCS	Minco HK6918 (payload) / Minco HK6900 (battery)	9

Operation concept: A preliminary spacecraft trajectory is designed based on the calculation of Lambert solver [5] with Solar gravity field only and the maximum time-of-flight (TOF) of 180 days considering the relatively short lifetime of most CubeSats. Given the low arrival ΔV (≤ 1 km/s) of COTS thrusters, the best launch window goes to March to May 2029 (indicated as a red box in Fig. 1).

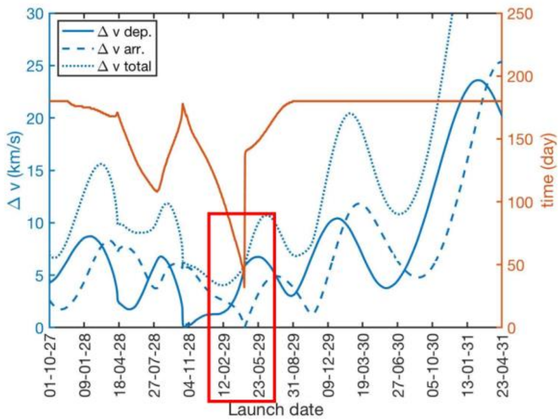

Figure 1. Estimated delta-v (departure, arrival and total) and TOF of the spacecraft versus the departure date. The red box indicates the best launch window.

Fig. 2 shows the trajectories of Earth, Apophis and the spacecraft from late 2027 to early 2031. Note that the orbit of Apophis is not stable, therefore it fails to converge as an ellipse as viewed from the top of the ecliptic plane. A tentative launch date is set on April 13th, 2029 based on the requirement of minimum arrival ΔV and TOF. We plan to have 4 stages throughout the mission:

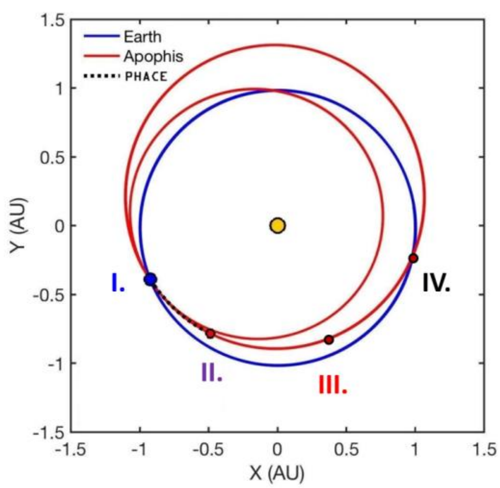

Figure 2. The trajectory of Earth (blue), Apophis (red) and PHACE (dash) and the corresponding mission stages.

I. Launch (2029.04.13)

PHACE will launch from Earth orbit and head to Apophis on April 13th, 2029. Given the departure ΔV ~5.6 km/s the spacecraft should arrive the destination with the TOF about 32 days.

II. Rendezvous (2029.05.15)

The spacecraft is scheduled to arrive Apophis on May 15th, 2029. After rendezvous, we will perform a global physical survey for around 45 days at the distance ~1200 m away from the asteroid (image resolution ~20 cm/px).

III. Approach (2029.06.30)

After the global survey, the spacecraft will approach Apophis to the distance ~500 m away and start the close proximity imaging of the surface with a high resolution ~8 cm/px.

IV. End (2029.08.13)

The entire mission is expected to end in the mid-August of 2029 with a lifetime of 120 days, yet it is possible to extend depending on the spacecraft condition.

Challenges: A main technic barrier of the mission is the high launch velocity impulse, which is difficult to realize by modern COTS thrusters for CubeSats. So far, the optimum propulsion is performed by iSat (Iodine Satellite) giving 4km/s ΔV with 5kg of iodine onboard 12U. The high moving velocity of Apophis is also an issue. By the time of rendezvous our spacecraft and Apophis will be ~40 lunar distances away from the Earth, and ~90 lunar distances by the end of the mission. A capable deep-space communication system will be crucial for efficient data transmission.

Summary: With limited payloads, PHACE can characterize the asteroid Apophis which is potentially threatening yet poorly understood. The practice of PHACE not only verifies the technology necessary to study PHAs in situ, but also demonstrates a low-cost, short-duration and high-feasibility operation of CubeSat missions in deep space.

Acknowledgments: We would like to thank Dr. H. R. Chen from Paris Observatory for valuable insights on advancing our mission trajectory design.

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