MIT Project Apophis:

Executive Summary

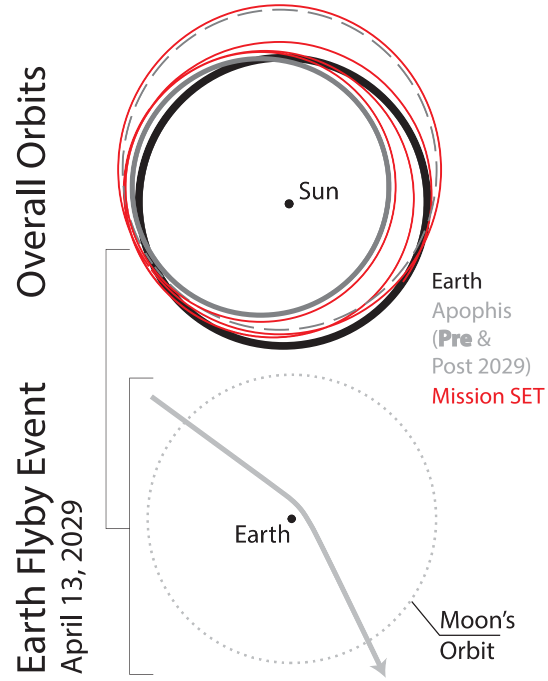
The **SET** Mission

Surface **E**valuation **& T**omography

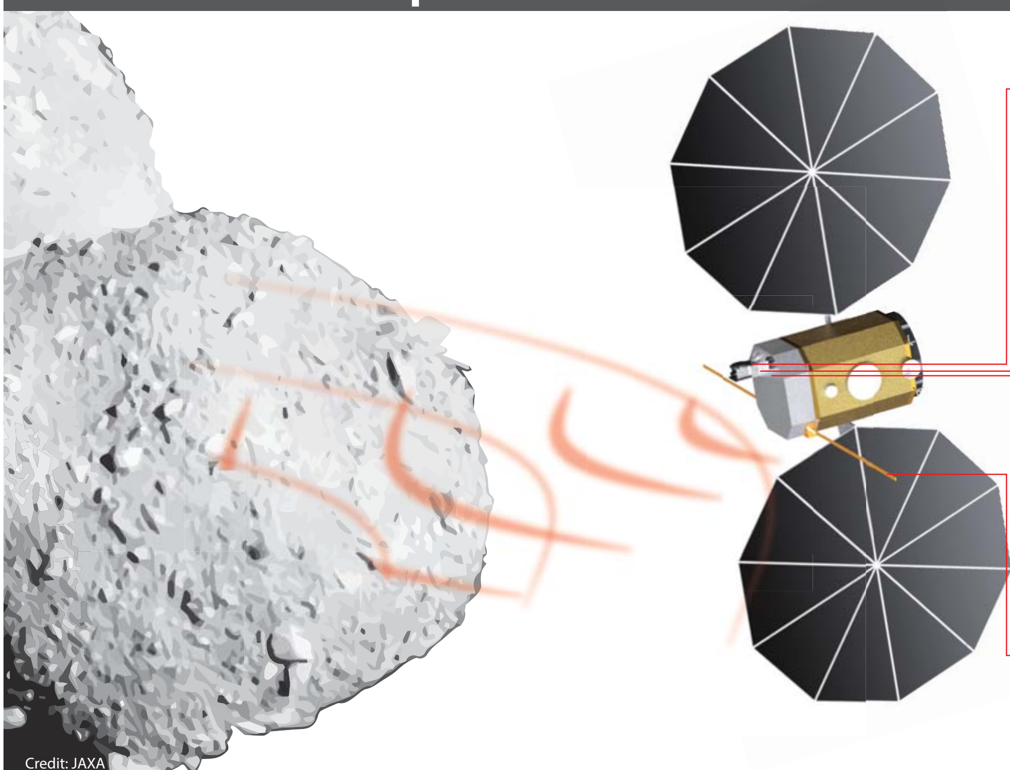
On April 13, 2029, the asteroid Apophis will pass by Earth at approximately 1/10 Lunar distance. This is a once-in-a-thousand year event in which nature is providing a direct experiment revealing how asteroid surfaces and interiors respond to tidal stress.

The asteroid Apophis is named after the Egyptian god of chaos and evil who was thwarted by the god Set riding a solar boat. Like Set, Mission SET will ride upon Solar Electric Propulsion to meet Apophis at which time the spacecraft will characterize the asteroid inside and out before and after the Earth flyby event.

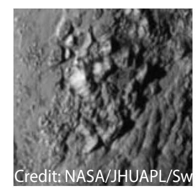
Launch: **August 2026**
Apophis Rendezvous: **March 2028**
Earth Flyby Event: **April 2029**
Tracking Mission Ends: **2033**



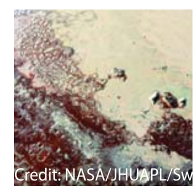
The SET Mission: Spacecraft and Instruments



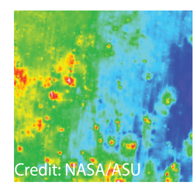
LORRI:
Pan-Chromatic (B&W) High Resolution Imager



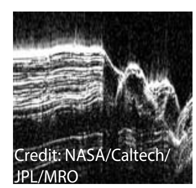
Ralph:
Color & Spectral Imager



TES:
Thermal Emission Spectrometer



RRT:
Radio Reflective Tomography



The SET Mission: The Objectives

Mission Objective 1:
Bulk Physical Properties

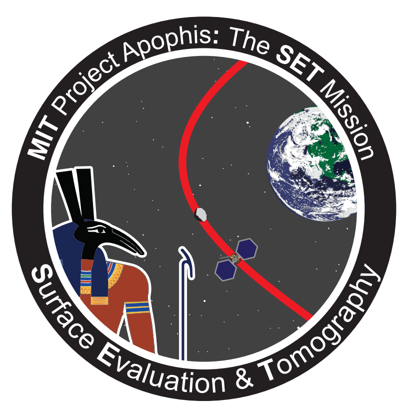
Focussed on the surface properties and orbital characteristics, this objective will improve the scientific community's understanding of asteroids as well as inform planetary defense strategies.

Mission Objective 2:
Internal Structure Changes

Measuring the internal structure of Apophis before and after an Earth Close Encounter will allow for a better understanding of not only how asteroids are constructed, but how tidal stresses affect them.

Mission Objective 3:
Yarkovsky Tracking

By following Apophis for multiple orbits and measuring the thermal emissions and orbital characteristics, the components of the Yarkovsky Effect can be decoded, improving our ability to track this Potentially Hazardous Asteroid.



Credit: MIT 16.83, Spring '17, Max Vanatta, Alissa Earle, Andrew Adams
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MIT Project Apophis: The SET Mission
Executive Summary

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May 24, 2017

1 Scientific Motivation

Achieving an understanding of asteroids and their impact hazard is one of the great responsibilities and grand challenges of our era. Natures is cooperating by providing a once-per-thousand year opportunity to study the outcome of an extremely close passage by an unprecedentedly large 350 meter (aircraft carrier-size) 20 million metric ton asteroid name Apophis on (Friday) April 13, 2029. Apophis' close encounter will be *inside* Earth's geosynchronous satellite ring at a near-miss distance of 5.6 Earth radii, less than one-tenth the lunar distance. While previous spacecraft missions have studied asteroids, none has ever had the opportunity to study "live" the outcome of planetary tidal forces on their shapes, spin states, surface geology, and internal structure. All of these physical parameters, and their changing response to induced stresses, represent an incredible opportunity to gain vital knowledge for addressing the eventuality of a known asteroid on an actual impact trajectory. In response to the imperative for knowledge and the once-per-many generations extraordinary "experiment" that nature itself is providing, we propose and outline a mission concept sending a spacecraft to orbit Apophis with the objectives of surveying its surface and interior structure before, during, and after its 2029 near-Earth encounter. The asteroid Apophis is named after the Egyptian god of chaos and evil. The proposed spacecraft is named SET, for the Egyptian god (Set) sent on his solar boat to thwart Apophis.

In recent decades, understanding of asteroids has been transformed from points of light to geological worlds owing to modern spacecraft exploration and state-of-the-art radar and telescopic investigations. Yet internal geophysical structures remain largely unknown. Understanding the strength and internal integrity of asteroids is not just a matter of scientific curiosity, it is a practical imperative for advancing knowledge for planetary defense against the eventuality of an asteroid impact.

The April 13, 2029 near-Earth flyby of Apophis will provide the opportunity for internal geophysical study as well as a chance to test current hypothesis on the effects of tidal forces on asteroids. Mounting theoretical studies [4, 7, 10, 12, 11, 13, 14] and physical evidence [1, 6], for tidal forces altering the shapes, spins, and surfaces of near-Earth asteroids all point to these Earth-asteroid interactions being as fundamental to the asteroid hazard problem as impact studies themselves.

The SET mission is motivated by additional factors and science objectives beyond the unique natural experiment opportunity. By including a thermal instrument and continuing to orbit Apophis after the Earth encounter, SET will be able to monitor and decode the coupling of rotation and thermal cycling resulting in Yarkovsky drift. Direct correlation of thermal properties with the resulting Yarkovsky drift is important for both future orbit predictions of Apophis as well as improving general understanding of asteroid dynamics. The SETs orbiter will also be able to map Apophis' global geology and composition and study its interior structure, increasing knowledge of mid-sized (100s of meter diameter) asteroids. Spacecraft studies of asteroids can provide insight into the geologic and dynamic history of the objects they study and not only improves our understanding of these individual objects but also has important implications for understanding solar system formation [5].

2 Mission Objectives

The SET mission achieves its science and hazard assessment goals through three key Mission Objectives (Table 1).

M.O.1 General Characteristics

The first mission objective focuses on the characterization of Apophis' bulk properties, including: shape, size, mass, volume, bulk density, surface topography and composition, rotation rate, and spin state and encompasses the surface geology and composition mapping goals. Surveying Apophis' surface geology and composition will help with understanding Apophis' geologic and dynamical history. Observations of these properties from throughout the encounter can be used to look for signs of tidal deformation and seismic resurfacing, as well as changes in spin state or rotation rate.

M.O.2 Internal Structure

The second mission objective is to characterize the internal structure before and after encounter. The strength and cohesion of Apophis' interior can be determined from observations of Apophis' interior structure and how it responds to the tidal torques from the Earth encounter event. This is useful information for both general asteroid studies and has implications for impact scenario modeling and planetary defense.

M.O.3 Orbit Characterization

The final mission objective studies the process of Yarkovsky drift. Post-encounter the spacecraft will continue to monitor Apophis until the next ground tracking opportunity in 2036. These synoptic measurements of position, rotation, and thermal emission will help decode the coupling of rotation and thermal cycling resulting in Yarkovsky drift. This will improve future orbit determination for Apophis and all potentially hazardous asteroids.

3 Science Payload

SET's science goals and mission objectives are accomplished with four instruments. The mission leverages heritage (with instruments based on those flown on the New Horizons, OSIRIS-REx, Mars Reconnaissance Orbiter, and Lucy missions) to provide a capable, robust instrument suite while keeping cost and risk low.

3.1 LOng Range Reconnaissance Imager (LORRI)

LORRI is a 20.8 cm Ritchey-Chrtien telescope with a 1024x1024 pixel panchromastic CCD imager (with a $0.29° \times 0.29°$ field of view) [2]. It will be the first instrument to be able to resolve Apophis during the spacecraft's approach. During this time it will work on improving upon ground-based measurements of Apophis' rotation rate, spin state, and shape, while also looking for potential hazards. Once the spacecraft is orbiting Apophis, LORRI will be responsible for high-resolution imaging of Apophis' surface, with $0.0099 m/pixel$ resolution at a distance of $2km$ from the asteroid's surface.

3.2 Ralph

Ralph consists of a panchromatic and color imaging camera (MVIC) and a special imager (LEISA).

Multi-spectral Visible Imaging Camera (MVIC) consists of 7 independent CCD arrays on a single substrate to produce panchromatic and colored images. Each CCD has a field of view of $5.7° \times 0.037°$, but works in time delay integration (TDI) mode to produce images with a much wider view [9]. MVIC will be responsible for broad panchromatic mapping of Apophis' surface once SET is in orbit, as well as color and broad band spectroscopy mapping, to look for signs of seismic resurfacing during Apophis' flyby of Earth.

Linear Etalon Imaging Spectral Array (LEISA) is a wedged filter infra-red spectral imager that creates spatially resolved spectral maps. LEISA is a scanning, imaging instrument, that makes use of

Table 1: Science Traceability Matrix for the SET mission

Top Level Mission Requirements	Science Goal	Science Measurement Requirement	Payload Requirement	Primary Instrument	Secondary instrument
M.O.1 - Characterize Apophis's shape, size, density, surface topography and composition, rotation rate, and spin state.	Surface Mapping (before, during, and after Earth encounter)	Survey Apophis' surface structure and shape to learn about geology of mid-sized (100's of meters diameter) asteroids	PLD.2	LORRI	Ralph-MVIC (pan)
		Survey Apophis' shape before and after encounter to determine the impact of tidal torques on an asteroid's shape	PLD.2	Ralph-MVIC (pan)	LORRI/Ralph-LEISA
		Measure Apophis' spin state and rotation rate before and after encounter to understand how tidal torques impact the dynamics of a potentially hazardous asteroid	PLD.2	Ralph-MVIC (pan)	LORRI/Ralph-LEISA
		Image Apophis' surface before, during, and after the encounter at sufficent resolution to observe possible land slides and other surface responses to tidal torques	PLD.3	LORRI	Ralph-MVIC (pan)
	Surface Composition Mapping (before, during, and after Earth encounter)	Map Apophis' surface with filters to allow for color imaging and broad band spectroscopy	PLD.4	Ralph-MVIC (color)	Ralph-LEISA
		Spectral mapping of Apophis' surface to look at compositional heterogeneities and better refine Apophis' spectral class with higher resolution and broader wavelength coverage than achievable with ground-based observations	PLD.1	Ralph-LEISA	Ralph-MVIC (color)
		Perform surface composition and color surveys both before and after encounter to look tidally induced resurfacing	PLD.1 & 4	Ralph	
		During encounter observe Apophis' surface with color filters at sufficient time and spatial resolution to observe tidally induced resurfacing	PLD.4	Ralph-MVIC (color)	Ralph-LEISA
M.O.2 - Characterize internal structure of Apophis before and after near-Earth event.	Internal Sturcture	Map Apophis' interior (before and after encounter) to interpret the strength and internal structure of a potentially hazardous asteroid	PLD.5	RRT	
			PLD.6	RRT	
M.O.3 - Characterize Apophis's orbit, accounting for the influencing factors of the Yarkovsky Effect.	Yarkovsky Effect	Post-encounter monitoring to decode the coupling of rotation and thermal cycling resulting in Yarkovsky drift	PLD.7	TES	LORRI/Ralph
Science Measurement Obective higlighted in blue are signficent for understanding how a potentially hazardous asteroid responds to tidal torques					

a special filter over which the wavelength varies in one direction. With wavelength coverage from 0.45 to $4.0\mu m$, spatial resolution of $60.8\mu rad$, and a $0.9° \times 0.9°$ field of view [9], LEISA will reveal compositional heterogeneities and any changes in surface composition that may be triggered by Apophis' tidal interaction with the Earth.

3.3 Radio Reflection Tomography Instrument (RRT)

The RRT instrument for SET will be based on the SHARAD instrument used on the Mars Reconnaissance Orbiter, and will consist of a $10m$ dipole antenna that can be folded for launch, and deployed solely with the elastic properties of the encasing tube, as well as an electronics box for signal generation and power amplification [8]. This method measures the differences in dielectric properties of materials in the asteroid by recording the echoes of transmitted low-frequency radio waves, thus providing a way of imaging the internal structure. The RRT instrument will have a transmission frequency of $20MHz$ and a bandwidth of $5MHz$. Assuming a refractive index similar to Itokawa, this bandwidth will provide a spatial resolution of approximately $20m$, a similar size to the Chelyabinsk meteoroid and thus significant from a planetary protection perspective.

3.4 Thermal Emission Spectrometer (TES)

TES will consist of a telescope, interferometer assembly, electronics, and support structure and achieves its spectral range by implementing an interferometer, beam splitter, and moving mirror assembly [3]. TES will map mineralogical and thermophysical properties of Apophis with a spectral range of 6 to $100\mu m$. TES uses a single detector with a field of view of $8mrad$, so at a distance of $2km$ it will have a field of view on Apophis surface of roughly $16m \times 16m$. TES can provide insight into Apophis mineralogy, globally map the material distribution, and determine regolith physical properties based on diurnal temperature measurements [3]. Most importantly, the thermal measurements from TES, combined with imaging and ground-based radar tracking, will help decode the coupling of thermal cycling and rotation which results in Yarkovsky drift, which will aid in not only refining future predictions of Apophis orbit, but also the orbits of other potentially hazardous asteroids.

4 Spacecraft

SET will utilize a LEOStar-3 bus, manufactured by Orbital ATK, which has heritage on the Dawn and Deep Space 1 missions (Figure 3.4).

Spacecraft Specifications:

- Length: $1.8m$ ($10m$ w/ RRT antenna deployed)
- Width: $1.8m$ ($18.6m$ w/ solar panels deployed)
- Height: $2m$

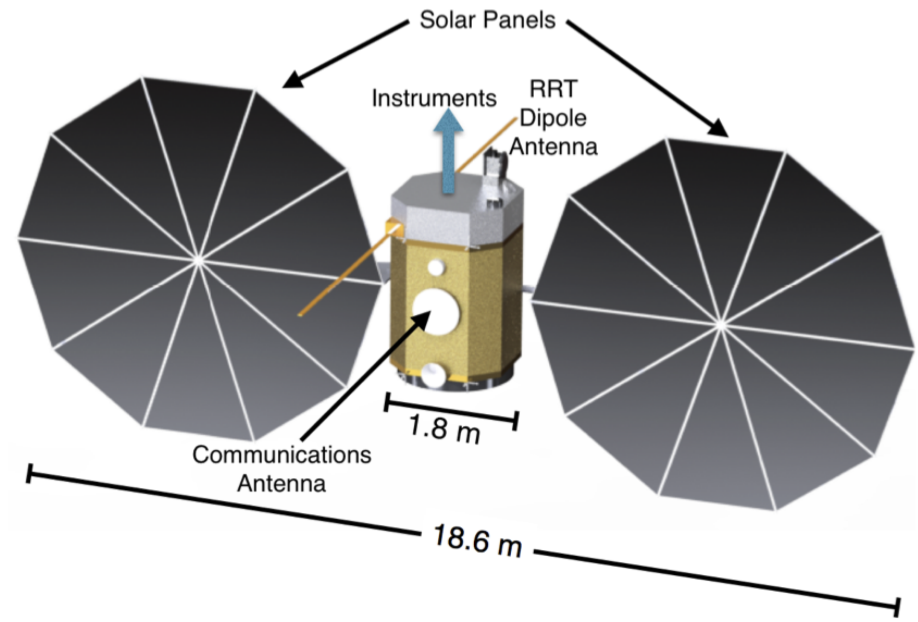

Figure 1: CAD Model of SET spacecraft layout. The instruments are all located at the top of the spacecraft to allow them to be used simultaneously. The RRT antenna and solar panels fold and are deployed after launch. (CAD Model by: Amy Vanderhout)

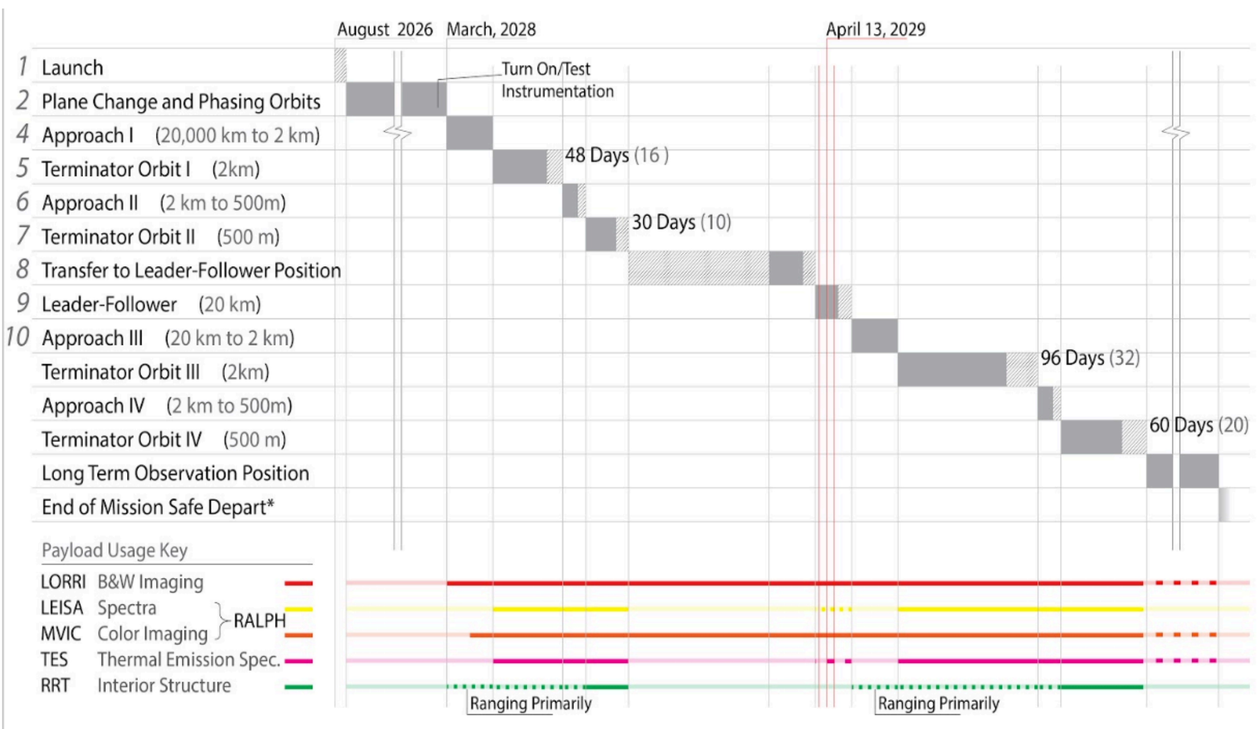

Figure 2: Proposed timeline of operations for the SET mission.

- Dry Mass: $633.5kg$
- Wet Mass: $1024.5kg$
- Power: two Orbital ATK Ultraflex solar panels

5 Concept of Operations

The SET Mission will **launch** in August 2026 within a 6 week launch window, with a back up launch window in August of 2027 (Figure 2). The spacecraft will calibrate its instruments as it exits the Earths Sphere of Influence and will use Solar Electric Propulsion (SEP), to gradually match its orbit with Apophis during the **plane change and phasing orbit phase**. In March 2028, the spacecraft will rendezvous with Apophis at its aphelion and begin the **Approach I phase**. During the Approach I phase the spacecraft will begin imaging with LORRI and then MVIC. This slow approach allows time for initial science observations and progressively maps the gravity field as SET enter Apophis' sphere of influence.

Once the spacecraft is $2km$ from the center of Apophis, it will enter a terminator orbit, beginning the **Terminator I phase**. This phase will consist of 15 orbits at $2km$, which are estimated to last for $48days$, and will serve as the initial characterization campaign of Apophis' surface for Mission Objective 1. Next, SET will enter **Approach II** and spiral down from the $2km$ orbit to a $500m$ orbit. For **Terminator II**, SET will orbit apophis in a $500m$ terminator for 30 days, ideal for the RRT instrument to study Apophis' internal structure for Mission Objective 2.

The spacecraft will then **transfer to leader-follower position** to prepare for Apophis' near-Earth flyby. For the **Leader-Follower phase**, SET will move to a position $20km$ ahead of Apophis, in order to observe Apophis from a safe distance and favorable viewing geometry during it's near-Earth flyby.

After the Earth Flyby Event, the spacecraft will complete a second set of **Approach** and **Terminator phases** to complete a second characterization campaign. Ideally, these phases would use the same orbital characteristics as before: using the imagers in the 2km orbit, then the RRT instrument in the 500m orbit. However, since there is uncertainty in the effect of Earths tidal forces on Apophis during the event, these details cannot be set for sure until after the encounter.

Once the second full characterization campaign is complete, the spacecraft enters the **Long-Term observation phase**, and will stay in formation with Apophis while using TES and the imaging instrument to decode and evaluate the Yarkovsky effect. The plan is to stay in formation with Apophis for at least 7 years. Finally, for the **End of Mission phase**, SET will perform an exit burn to leave Apophis sphere of influence, entering its own heliocentric orbit, compliant with all constraints for planetary protection.

6 Conclusions

The SET mission will take advantage of the incredible opportunity nature is providing to study the impact of tidal interactions on potentially hazardous asteroids. The mission will launch August of 2026 and arrive at Apophis in March of 2028, allowing for thirteen months of initial characterization before the April 13, 2029 Earth encounter event. The SET mission shows that a scientifically robust mission is well within the range of currently available high heritage proven flight hardware and launch capacity. The science results can directly inform future studies of asteroid impact mitigation, including long-term tracking correlating measured thermal emission and the corresponding Yarkovsky drift.

Acknowledgments

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