CHARACTERIZATION OF ASTEROID THERMAL ENVIRONMENTS AND PHYSICAL PROPERTIES FOR EXPLORATION AND PLANETARY DEFENSE USING ADVANCED THERMOPILE ARRAYS.

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Introduction: The asteroid, 99942 Apophis, will approach within a ~0.1 lunar distance, or ~36,700 km, from Earth on April 13, 2029. Being the only Potentially Hazardous Asteroid (PHA) to approach Earth in this close of proximity before the year 2200 also makes the flyby a unique and crucial opportunity to gather information to prepare planetary defense strategies. Further important measurements to be made by an Apophis 2029 mission will require amongst its instrument payloads a thermal infrared imaging spectrometer. Asteroid thermal environments can be extreme with equatorial regions experiencing diurnal temperatures of ~200 to ~400 K for fast-rotating, near-Earth asteroids, with larger ranges expected for slow-rotators. Detailed characterization of the surface requires high quality thermal imaging with an ability to obtain highly accurate temperature measurements across the full range of thermal environments present on the surface. To meet these requirements, our investigation will utilize instruments with all reflective optics and advanced thermal infrared detectors. Specifically, we will utilize the same thermopile technology successfully employed at the Moon by the Diviner Lunar Radiometer (Diviner) on the Lunar Reconnaissance Orbiter (LRO) and at Mars by the Mars Climate Sounder (MCS) on the Mars Reconnaissance Orbiter (MRO).

Objectives: Potential investigations would broadly fit in the following four areas, with appropriate modifications for specific asteroid properties.

1) Characterize the diurnal thermal environment at all latitudes, including the spin axes.
2) Map and characterize regions (at scales down to cms) where complex organics and water-ice may be thermally stable on surface or in the subsurface.
3) Characterize the local thermophysical properties, including the distribution and abundance of rocks on the surface and in the near subsurface.
4) Characterize local compositional properties and abundance of silicates, oxides, hydrated minerals, organics, and volatiles.

Since Apophis is an Sq-type, not all of the above are relevant to Apophis, but may be applicable to PHA of other types in the future.

Our approach is based on the fact that the thermal infrared provides both unique and complementary information on environment, physical properties, and composition that are critical for addressing high-priority science questions. Therefore, it is critical that a highly capable thermal infrared instrument be available for future asteroid surface exploration and planetary defense missions like Apophis 2029.

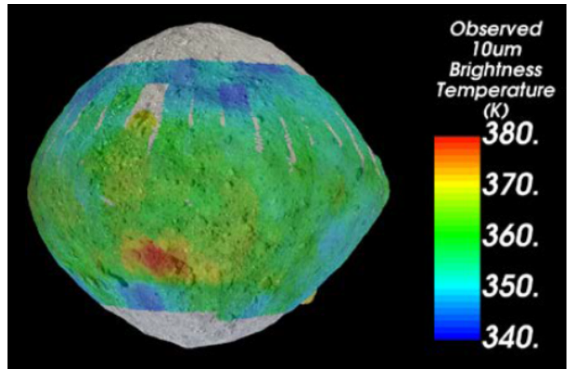

Figure 1: *10-μm brightness temperatures of Bennu as observed by OSIRIS-REx's OTES [10].*

Thermal Environment. At the most basic level, and like all thermal infrared radiometers, our instrument is a thermometer. Although the surface expression of temperature is a balance between endogenic and exogenic sources, we know from existing lunar measurements that the actual thermal behavior is quite complex, including significant effects from topography, thermophysical properties, and albedo at a wide range of spatial scales [e.g., 1-6]. To fully characterize the diurnal thermal environment, the minimum detectable temperature of our instrument must be lower than the lowest temperature expected to be relevant. Thermopiles offer the only demonstrated means of measuring extremely low temperatures (i.e., <100 K) with a non-cryogenic detector, which significantly lessens power consumption requirements.

Cold Traps: Areas near the asteroid axis or rotation (i.e., "polar regions") contain particularly interesting thermal environments. For asteroids with low spin axis inclinations, significantly lower temperatures may be present due to persistent or permanent topographic shading. Thus these areas could be important for cold-trapping complex organics and volatiles. Next-generation thermopile detectors are more sensitive than those used in Diviner, which has already provided unprecedented thermal maps of the lunar polar regions at scales of hundreds of meters [1, 6]. Therefore, our instrument would be capable of accurately measuring temperatures below 50 K at cm-scales for close-range observations. Understanding the difference between accessible, sub-meter-scale shadowed regions is critical to understanding volatile stability, sources, and potential resources, and is only readily identified by their temperature.

Thermophysical Properties. Measurement of variations in temperature with time, is key to understanding the thermophysical properties of airless body surfaces. Invariably a scene is composed of a surface exhibiting many temperatures both due to variation in the local incidence angle of the Sun, and by differences in thermophysical properties and albedo. Because of the temperature variations, the spectrum of a pixel that includes these many temperatures will deviate from the spectrum of a pure blackbody. Therefore, multispectral measurements can be used to detect temperature units at the subpixel level. For example, in the case of Moon the relative abundance of rocks and soil [2], regolith thermal inertia [5], and surface roughness [4] have been determined from multispectral thermopile measurements used to characterize the deviation from pure blackbody behavior.

Composition: Most geologic, organic, and cryogenic materials have strong absorption and transmission features in the mid- and/or far-infrared that can be used to determine the bulk composition of the surfaces where they are found. In the case of the Moon, Diviner used three narrow mid-infrared passbands near 8 microns to characterize the bulk silicate mineralogy found on the lunar surface, including a high concentration of silica and iron found in localized volcanic features [e.g., 7-9]. Compositional constraints from thermal-infrared techniques would be much stronger with additional spectral information from the airless body surfaces. To measure compositional properties requires multiple passband channels at specific wavelengths where materials with asteroid compositions can be discriminated.

Instrumentation: Given the focus on thermophysical properties and composition, the excellent performance of thermopiles for this environment, our instrument is based on this technology. Continued development since MCS and Diviner has led to higher density arrays that will fly in 2020 on the Polar Radiant Energy in the Far-InfraRed Experiment (PREFIRE) mission and that were also previously advanced to TRL 6 for the harsh thermal and radiation environment found at Europa via ICEE funding. The specific instrument implementation is flexible depending on the opportunity and programmatic risk posture (Table 1).

Near Build-to-Print Copy of Diviner. The simplest implementation would be to re-fly Diviner with small modifications in the filter passbands to reflect the science objectives of the target asteroid. Diviner's dual actuators give it the ability to scan and image any proximal scene, which it demonstrated on orbit by taking a "portrait" of LRO. However, this is also the highest mass and cost option and would offer more limited spatial resolution.

Advanced Articulating Pushbroom Imager. Investments in thermopile technology have resulted in larger format arrays at varying levels of development from TRL4 (128x64) through TRL8 (64x8). These advanced arrays enable higher spatial resolution for similar scale optics. The new arrays are also compatible with single telescope systems and flight proven, lower-mass articulation systems, which provides a significant reduction in mass and cost while providing superior performance.

Wide Field of View Full-Frame Imager. The technologies required to produce a full 2D thermopile array without the gaps between elements used in the pushbroom designs has been demonstrated to TRL4. An instrument built around this technology could be paired with a filter wheel and wide field of view optics to provide a unique combination of capabilities and enable the rapid acquisition and interpretation of thermal data.

Table 1: Instrument Architectures

	Diviner	Advanced Articulating Pushbroom Imager	Wide FOV Full-Frame Imager
Mass	10 kg	<5 kg	<3 kg
Power	12 W	<10 W	<7.5 W
Detector	Dual Telescope 21x6 & 21x3	64x8 to 128x64	2D 128x64 (no gaps)
IFOV	3.4 x 6.7 mrad	<1 mrad	5.4 mrad
Spectral Range	0.3 to 400 microns	0.3 to 200 microns	0.3 to 200 microns
Spectral Channels	9	8 to 16+	6 to 10

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