Advances in Solar System Science: Research Enabled by 2.4 – 25 µm Spectroscopy with SOFIA

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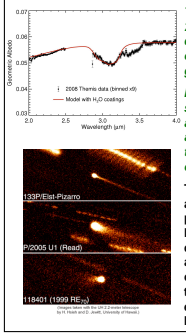
Introduction

Low to medium resolution spectroscopic capability (R~100 to 1500) in the 2.4 to 25 micron spectral range is a key need for planetary astronomy that would enable investigation of many of the most important open questions regarding the Solar System. In particular, *surface compositions* of small bodies across the Solar System hold critical clues to the variety of processes that combined to form and evolve the Solar System. Current understanding of these compositions suffer from the difficulty of obtaining high quality spectra at $\lambda > 2.4$ microns from the ground, a problem that arises largely from obscuration by water vapor in Earth's atmosphere. Here, we highlight recent results in small bodies research that illustrate potential advances in planetary astronomy that will be enabled by retaining and expanding SOFIA's spectral capabilities in the 2.4 – 25 µm spectral range.

2.4 – 5 µm Reflectance Spectra

Ice on outer Main Belt asteroids

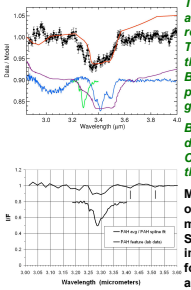


Top: Spectrum of asteroid 24 Themis showing the discovery of a thin coating of H_2O ice on surface grains.

Bottom: Images of several small, outer Main Belt asteroids with comet-like appearance, suggesting the presence of H_2O ice at or near the surface.

These discoveries indicate a possible widespread presence of ice in the Main Belt. Mapping the distribution and abundance of this H_2O is critical for understanding the formation and evolution of the building blocks of the planets.

Complex organics on primitive surfaces

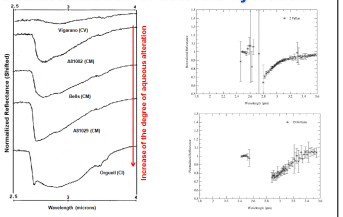


Top: Spectrum of asteroid 24 Themis after removal of H2O model. The red curve is ice tholin, blue is the Cold Bokkveld meteorite, purple is asphaltite, and green is PAH.

Bottom: Spectrum of the dark side of Iapetus from Cassini/VIMS, showing the discovery of PAHs.

Mapping the distribution of complex organic material in the Solar System, as with H2O, has important implications for planetary evolution and the delivery of prebiotic material to early Earth.

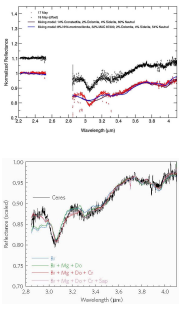
Characterization of asteroid hydration



Left: Spectra of meteorites showing spectral variations due to differences in degree of alteration. Right: Asteroid spectra obtained from the ground. The absorption peak near 2.7 µm cannot be observed from the ground.

Understanding the hydration state of asteroids is crucial for models of the chemical and thermal evolution of the Solar System.

Carbonates on asteroids

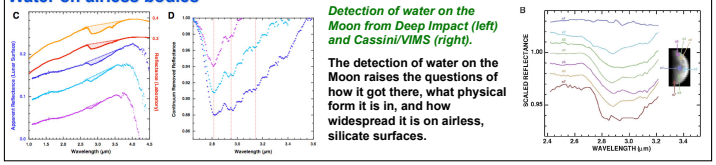


Top: Spectrum of Ceres, displaying several unusual absorption bands, including those of carbonates.

Bottom: The same spectrum of Ceres, now compared to a mixture that includes brucite, a hydroxide consistent with high temperature alteration of olivine.

The thermal and aqueous alteration history of Ceres may be different than that recorded in carbonaceous chondrite meteorites. It is unclear whether this history is unique to Ceres.

Water on airless bodies

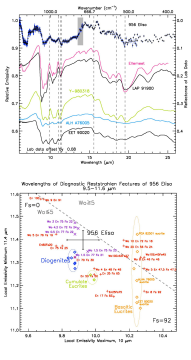


Detection of water on the Moon from Deep Impact (left) and Cassini/VIMS (right).

The detection of water on the Moon raises the questions of how it got there, what physical form it is in, and how widespread it is on airless, silicate surfaces.

5 – 25 µm Thermal Emission Spectra

Basaltic asteroids

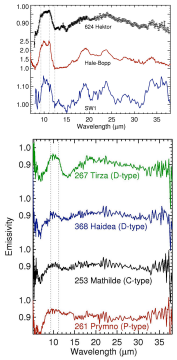


Top: Spectral emissivity of the asteroid 956 Elisa and several basaltic meteorites.

Bottom: Positions of restrahlen features of pyroxenes and meteorites of varying compositions. Elisa plots near those that are relatively high in Mg and low in Ca.

Thermal-IR emissivity spectroscopy enables investigation of the stratigraphy of Vesta by observing family members and differentiation in different parts of the Solar System by studying other basaltic asteroids.

Primitive asteroids

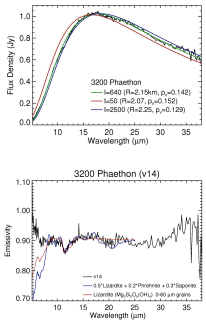


Top: Spectral emissivity of the Trojan asteroid 624 Hektor and two comets. The surface of Hektor appears to be composed of fine grained silicates of similar composition to those in comets.

Bottom: Emissivity spectra of several other primitive asteroids, showing variation diagnostic of composition and surface structure.

Primitive asteroids display no (or only very weak) absorption bands at shorter wavelengths. Thermal-IR spectra are the only means of measuring compositions of these objects, the most abundant asteroid type.

Near-Earth objects

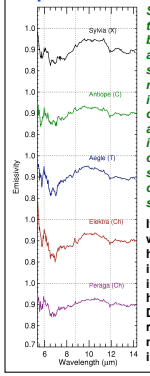


Top: Thermal flux spectrum of Phaethon, along with model fits demonstrating a fairly high thermal inertia.

Bottom: Emissivity spectrum of Phaethon, and fits to lab spectra of hydrated silicates.

Determining compositions of near-Earth objects is key to unraveling dynamical mixing in the inner Solar system and has important implications for the material that is delivered to Earth as well as the potential resources available for human use.

6.2 µm feature



Spectral emissivity of several of the brightest asteroids observed by Spitzer/IRS. Nearly all asteroids observed by Spitzer show a narrow emissivity peak near 6.2 µm. Possible materials include hydrated silicates, organics, anhydrous silicates, and carbonates. The most likely in terms of position and lack of other features is hydrated silicates, but the feature occurs on asteroids that show no other sign of hydration.

If due to hydrated silicates, this would imply far more widespread hydration than currently imagined, with significant implications for the thermal histories of small bodies. Detection of water on the Moon raises another possibility – minor contamination by implanted solar wind.

Summary & Recommendations

- ☆ Asteroid compositions provide the clearest windows into the formation and evolution of the Solar System
- ☆ The majority of asteroids remain largely uncharacterized because diagnostic mineralogic features lie in spectral regions not accessible from the ground, mostly because of terrestrial water vapor
- ☆ Retaining and improving SOFIA's spectral capabilities in the 2.4 to 25 µm region will open new wavelength regions to asteroid studies, promising significant advances in planetary astronomy
  - ★ Features are generally broad, so low to medium spectral resolution (R~100 to 1500) is ideal
  - ★ High sensitivity (for characterizing many objects and weak features) is more critical than high resolution
- ☆ The potential investigations enabled directly address several NASA strategic goals regarding Solar System exploration as stated in the *Solar System Exploration Roadmap*, including
  - ★ "How did the Sun's family of planets and minor bodies originate?"
  - ★ "How did life begin and evolve on Earth, and has it evolved elsewhere in the Solar System?"