LUNAR WATER, ASTEROIDAL OBSERVATIONS: IMPLICATIONS AND OPPORTUNITY.

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Asteroidal Observations

Water- and OH-bearing minerals (hereafter called “hydrated minerals” for simplicity) are commonly found in carbonaceous chondrite meteorites. These minerals are also commonly found on Earth, and are the result of aqueous alteration of silicates. Some of the carbonaceous chondrites have the equivalent of 10% or more water by weight [1].

The C-class and related asteroids have long been associated with the carbonaceous chondrites [2]. Many of these objects also show evidence of hydrated minerals, with diagnostic spectral features in the 3-µm region. Some asteroids, like 2 Pallas or 13 Egeria, have spectra that are reminiscent of what is seen in the meteorites [3], while others, like 1 Ceres or 24 Themis, are unlike any meteorites in the 3-µm region but have interpretable spectral features identified with specific hydrated/hydroxylated compositions [4-5].

While the identification of hydrated minerals on C asteroids is relatively easy to understand and uncontroversial, these same spectral techniques have found evidence for their presence on other, more unexpected objects. In many ways, the most notable of those objects are the M-class asteroids. Long associated with the iron meteorites, observations by Jones et al. [6] showed that two of them had 3-µm bands. Follow-up work [7-8] found several additional such objects, preferentially among the largest M asteroids. This has been interpreted as evidence for hydrated minerals and evidence that the M asteroid class is a heterogeneous one, containing many different compositional types. Although Gaffey et al. [9] invoked difficulties of observing at these wavelengths to explain these data, the unusual nature of the “hydrated Ms” has been borne out by other studies including polarimetry, radar, and mid-IR observations [10-13].

While the M-class asteroids are the best documented of these “unexpectedly hydrated” objects, there are others. A weak absorption band was also reported on 4 Vesta [14] contrary to expectations given the very anhydrous nature of the HED meteorites, which originated on Vesta. Additional observations [15] could not rule out a very shallow band, but it was thought more likely a change in continuum level was responsible. Some S-class asteroids (notably 6 Hebe), also expected to be anhydrous based on meteorite analogs, have also been observed with 3-µm bands [16], though attempts to confirm the observations have not been successful.

Lunar Water

For much of the last decade, fierce debate has been conducted about whether the lunar poles harbor ice, culminating in the LCROSS mission. While the search for ice at the lunar poles has been at center stage, the lunar regolith at lower latitudes and in sunlit areas has long been characterized as dry. However, results centering on lunar water derived from three spacecraft observations (each with differing strengths and limitations) have recently been published. M^3 on the Indian Chandryaan-1 spacecraft, VIMS on Cassini and the Deep Impact (DI) High-Resolution Instrument–infrared spectrometer all have observed the Moon in the 3-µm region either from orbit or during flbys [17-19].

Data from all three of these spacecraft agree that in daylight the Moon has a 3-µm band, interpreted as water and/or OH, widespread across its surface. The M^3 data, restricted to high latitudes due to the thermal flux removal issues, shows little difference in band depth between highland and mare regions, though greater band depths are associated with “fresher” craters. The Deep Impact data shows weaker bands near local noon, with stronger absorption in early morning and late afternoon. While both highland and mare regions always have the band to some depth, the variation in the maria was seen to be greater than for highland material. This is most easily explained as changes with temperature, though Clark ([19] in Supporting Online Material) argued that photometric effects complicate the situation.

The independent observation of 3-µm bands on the Moon by these three spacecraft was very surprising given the previously described understanding of the lunar surface as dry. While this work is very new, and interpretations are continuing to evolve, the early consensus seems to be that the band is due, at least in part, to adsorbed water and OH likely created by the interaction of solar wind protons with silicates in the lunar regolith.

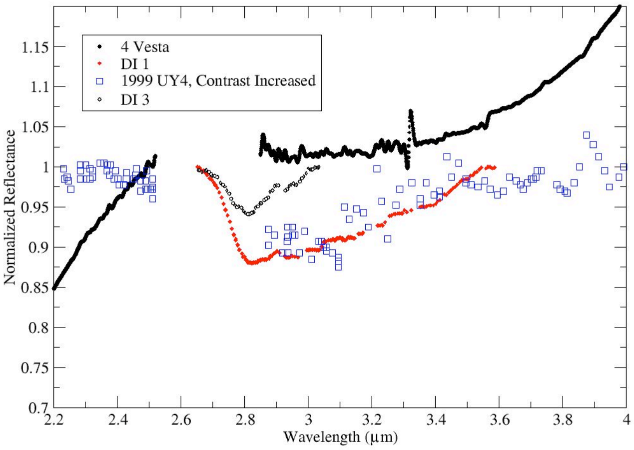

Figure 1: Observations of Vesta, taken at the IRTF using SpeX and published in Rivkin et al. (2006). The "DI" points are from Sunshine et al. (2009). While the Earth's atmosphere does not allow useable data from groundbased observations between 2.5-2.85 µm (missing region in Vesta data), the DI observations show the water band is broad enough to be observable in SpeX data. The open blue points show 1992 UY4 (Volquardsen et al. 2007), with its band contrast mathematically increased. This object shows a qualitatively similar 3-µm band shape to the lunar observations. The Vesta data are not thermally corrected (thus the increasing flux beyond 3.5 µm), but these whole-disk, low phase angle observations do not show a measureable 3-µm band. Thermally-corrected data also do not show a measureable 3-µm band on Vesta.

Asteroids and the Moon: Mutual context and constraints

The presence of water on the lunar surface potentially reopens interpretations of asteroidal (and other small body) surfaces. However, the small bodies also provide an opportunity to better understand the lunar results. There is already a body of observations that can be used to explore conditions not seen on the Moon in order to help constrain the formation of lunar water. For instance, NEOs can be followed as they experience a range of temperatures and phase angles to investigate photometric effects. Interestingly, the only NEO known to have a 3-µm band, 1992 UY4 [20], has a band shape reminiscent of a low-contrast version of what is seen on the Moon (Figure 1). Vesta is a basaltic body like the Moon, and the lack of a deep band on its surface (also Figure 1) must be considered when interpreting the lunar results. Phobos and Deimos also present similar conditions to the Moon, save for temperature (and a primary with a strong magnetic field).

We will discuss the current state of interpretations of asteroidal water/hydroxyl, the degree to which the discovery of lunar water requires a reassessment of the literature, and also assess prospects for using the asteroidal data to provide context and insight to the lunar results.

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