Spectroscopy and Asteroid Interiors: Judging a Book When All You Have Is Its Cover. A. S. Rivkin[1], [1]JHU/APL, Laurel MD USA (andy.rivkin@jhuapl.edu),

Introduction: The asteroids contain information about the earliest times in solar system history, information now lost from the larger satellites and planetary bodies. There is evidence from meteorites that the objects now in the asteroid belt experienced a range of thermal histories ranging from high-temperature melting and differentiation to objects that remain today much as they were at formation [1]. The population of asteroids spans a large range in size, formation location, etc., and by understanding the distribution of thermal histories through the asteroid belt, we can get insight into the prevalent conditions in the inner solar system. The primary way we constrain the thermal history of a given asteroid or group of asteroids is through compositional studies that link them to the meteorite samples in our labs, and/or identify minerals whose formation conditions can be estimated. In turn, the primary way we obtain asteroid compositions is via reflectance spectroscopy.

There is a long history of using reflectance spectra to determine whether an asteroid is likely differentiated or chondritic and undifferentiated. It was recognized quickly that Vesta's spectrum was well-matched to that of the differentiated HED meteorites [2], but other conclusions were harder to reach. Early studies focused on searches for spectral variation either on a single body, with the expectation that such variation would most likely be due to compositional differences [3], or among members of collisional families, expecting that objects representing the cores, mantles, and crusts of differentiated objects would be readily identifiable [4]. However, the recognition that space weathering processes operated on asteroid surfaces makes it possible that variation on a single body could be due to different amounts of weathering [5] and even the large spectral surveys around the turn of this century did not identify any collisional families easily interpretable as arising from a differentiated parent body [6,7].

With the availability of more sophisticated compositional modeling techniques, the effects of space weathering can be accounted for and mineralogies can be more precisely measured—for instance, the asteroid Itokawa was correctly interpreted as a space weathered LL chondrite [8], as confirmed in spectacular fashion by the Japanese Hayabusa mission [9,10].

While great effort has been applied to studies in the 0.5-2.5 μm spectral region, several materials critical to our understanding of asteroid differentiation are featureless in this spectral region: iron-nickel metal that could signify a liberated core [11], and the low-albedo, carbonaceous material that characterizes most objects in the main asteroid belt [12]. Observations in the 2-4 μm region, sensitive to OH and other volatiles, can also provide insight into the distribution of differentiated asteroids, and will be the focus of the presentation.

Themis and Icy Asteroids: In addition to the rock-metal differentiation familiar to us from the meteorite collection, models of Ceres show that ice-rock differentiation may be expected in large objects that accreted with sufficient water [13-16]. The observed cometary activity of several small outer belt "activated" asteroids (including several objects in the Themis collisional family) demonstrates the presence of ice in their near surface [17,18], and an absorption on 24 Themis and 65 Cybele near 3.1 μm has been interpreted as due to ice frost [19-21]. However, it is not yet clear whether the ice represents primordial ice from an undifferentiated object or if it is exposed from the mantle of a differented object [15,16] It has been noted that aqueous alteration reactions are exothermic, and we might that once the reactions begin they will continue until all available ice is consumed [22]. In this case the continued presence of ice (as constrasted with hydrated minerals or other alteration products) would suggest an object is undifferentiated. However, others argue there are multiple reactions that can result in aqueous alteration, and it is not clear that all of them must be exothermic, creating the possibility of co-existing ice and hydrated minerals.

In addition, the presence of ice is itself still somewhat controversial, and an alternative identification of the band as goethite has been proposed [23], though it seems less consistent with the relationship between the activated asteroids and Themis. The sublimation timescale for ice is relatively short at the temperatures typical for Themis, and resupply may be necessary for frost to be present on its surface. If instead of an undifferentiated object, the Themis family parent body was differentiated like Ceres, a large reservoir of ice may be available to provide the observed ice. As additional objects with Themis-like spectra are identified [24], further constraints will be possible.

M is for 'Mess': M-class asteroids have long been interpreted as the most-likely parent bodies for iron meteorites [25]. However a series of observations demonstrated that the class is heterogeneous in composition [26-32] The finding that a significant fraction of large M asteroids have 3-μm absorptions weakened the connection to iron meteorites, though it left unanswered the question of what these "wet Ms" or "W asteroids" actually were. In the intervening decade, new meteorite groups have been identified which may be appropriate analogs to the Ws (the CH meteorites: [33], radar studies have found most (but not all!) Ws have lower radar albedos than M asteroids without 3-μm bands (also simply called "Ms") [34], and a combination of collisional and dynamical modeling has led to the suggestion that iron meteorite parent bodies originated interior to the present asteroid belt in a population now largely extinct [35]. The Rosetta spacecraft's flyby of the M/W asteroid Lutetia led to a flurry of support observations, with the surprising result that Lutetia appears to have large-scale spectral variation on its surface [36-38]. While it may appear that we are no closer to finding the large numbers of iron meteorite parent bodies the meteorite collection may suggest are out there, hope springs eternal.

Caveats and Confounding Factors: One reason that hope springs eternal is that work continues on a number of fronts. If we have learned anything from decades of asteroid spectroscopy, it's that reality is always more complicated than we can appreciate. The revolution in asteroid dynamics unleashed by the rediscovery of the Yarkovsky Effect and the development of the Nice Model (and parallel efforts to develop alternate models) forces us to reexamine our expectations about current vs. formation locations. Similarly, the discovery of OH on the Moon and Vesta [39-42], and the interpretations of those observations, force us to reconsider our interpretaions of surface compositions. I will attempt to cover the current state of affairs and not serve as a further confounding factor, myself!

Acknowledgments: This work was partially supported by the NASA Planetary Astronomy Program.

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