OUTER MAIN BELT ASTEROIDS: IDENTIFICATION AND DISTRIBUTION OF FOUR SPECTRAL GROUPS.

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Introduction: On the basis of spectral analysis in the 2-4-µm region, [1] characterized the 3-µm band *shape* in 17 outer Main Belt asteroids, showing a spectral diversity among these objects. Here we expand this analysis to include spectra in the visible (~0.4-0.93-µm) and the near-infrared (NIR: 0.9-2.5-µm) regions. The analysis of the former region, which includes the 0.7-µm feature, will complement our interpretation of the 3-µm band. In the latter region, we will investigate any anhydrous silicate features that may be present. Hence, our comprehensive analysis will include a complete spectral region, the visible and near-infrared (VNIR: 0.4-4.1-µm), which will provide more insight about outer Main Belt asteroids and their thermal evolution. NIR spectra of asteroids analyzed thus far have revealed an interesting trend spanning the 2.5 < a < 4.6 AU region. Four spectral groups are identified in this region: the Ceres-like group, the sharp OH group, the rounded H_2O group, and the featureless group.

Observations & Data Reduction: We collected asteroid spectra between April 2009 and December 2010, using both the prism (0.8-2.5-µm) and the long wavelength cross-dispersed (LXD) (1.9-4.1-µm) modes of the SpeX spectrograph/imager at the NASA Infrared Telescope Facility (IRTF). Spectra of a G-dwarf standard star, which has solar-like temperatures and spectral slopes, were also obtained for each asteroid to remove telluric water vapor absorption features. For data reduction, we used Spextool, a set of Interactive Data Language routines provided by NASA IRTF.

Results: Our observations include asteroids with different classes (C, P, D, G, and T), diameters (~99-400-km), and families/groups (Hygiea, Themis, Cybele, and Hilda). On the basis of the 3-µm band *shape*, these asteroids were classified into four spectral groups:

Ceres-like group. The first group consists of one asteroid: 10 Hygiea. This asteroid, which is the main member of the Hygiea family, has a spectrum similar to Ceres's spectrum [2] (Fig. 1). 10 Hygeia's spectrum exhibits a 3-µm feature with a band center at 3.05±0.02-µm, which is 8.2% deep and superimposed on a broader absorption from ~2.8-µm to 3.7-µm. This finding suggests that Ceres's surface mineralogy is not unique. [3] showed that the spectral features of Ceres can be attributed to the presence of the hydroxide brucite, magnesium carbonates, and serpentines. The spectrum of 324 Bamberga obtained by [4] could also be interpreted as another possible Ceres-like spectrum.

Sharp OH group. The second group includes eight asteroids: 121 Hermione (Cybele group), 104 Klymene (Themis family), 48 Doris, 308 Polyxo, 36 Atalante, 187 Lamberta, 54 Alexandra, 34 Circe, and 91 Aegina. These asteroids have spectra that exhibit a sharp OH 3-µm feature, suggesting the presence of hydrated silicates on their surfaces (e.g., Fig. 2). We have noted that most asteroids with sharp OH 3-µm features are concentrated in the 2.5 < a < 3.3 AU bin in agreement with the work of [5] who suggested that asteroids in this region have undergone a widespread aqueous alteration episode early in the solar system history. [5] also suggested that hydrated silicate abundance declines gradually among asteroids with increasing heliocentric distance.

Rounded H_2O group. The third group consists of three asteroids: 76 Friea (Cybele group), 790 Pretoria (Cybele group), and 401 Ottilia (Cybele group). These asteroids have spectra that exhibit a rounded H_2O 3-µm feature, suggesting the presence of water ice on their surfaces (e.g., Fig. 3). We have noted that these three asteroids are concentrated in the 3.3 < a < 3.6 AU bin. The spectra of 24 Themis, located in the same bin, were also found to exhibit H_2O 3-µm feature by [6, 7]. Additionally, [8] found that 65 Cybele, also located in the same bin, exhibits the H_2O 3-µm feature as well.

Featureless group. The fourth group includes 4 asteroids: 152 Hilda (Hilda), 361 Bononia (Hilda), 334 Chicago, and 107 Camilla (Cybele). These asteroids are located in the 3.6 < a < 4.6 AU bin that includes the 3:2 resonance with Jupiter at ~4.0 AU. The spectra of these asteroids were found to be featureless. [9] proposed a trans-neptunian origin for some asteroids in this bin, which is populated mainly by P- and D-type asteroids. It is possible that some of these asteroids' surfaces contain considerable amounts of hydrosilicates/water ice that are masked by opaque minerals such as magnetite and carbon-bearing phases.

Thermal Evolution of Outer Main Belt Asteroids: When placed in context with the thermal model of [10], the 3-µm band *shape* analysis reveals a remarkable trend, which will lead to very appealing hints about the alteration histories and thermal evolution of outer Main Belt asteroids spanning the 2.5 < a < 4.6 AU region (Fig. 4). The thermal model of [10] suggests that planetesimals accreted closer to the Sun and hence earlier would have larger proportions of live ^{26}Al available to drive heating, responsible for aqueous alteration in CM/CI chondrite parent bodies. Fig. 4 illustrates that most asteroids with the sharp OH 3-µm feature are concentrated around the vertical bar at 2.7 AU, which marks the approximate boundary between bodies that melted or were metamorphosed and those experienced melting of ice and subsequent aqueous alteration. Fig. 4 also reveals that asteroids with the rounded H_2O 3-µm feature, including 24 Themis and 65 Cybele, are concentrated around the vertical bar at 3.4 AU, which indicates the transition to unaltered asteroids that might still contain water ice. The previous analysis is being expanded to include the VNIR region, for a deeper understanding of the phyllosilicates, any anhydrous silicates, and the opaque/carbonaceous component of the surface of these asteroids.

Summary: When coupled with laboratory analyses of CM/CI chondrites, this finding will lead to constrains on how, when, and where aqueous alteration occurred in outer Main Belt asteroids, and will offer a unique glimpse at the effects of asteroidal processing on early solar system materials. Further work will include petrology, geochemistry, and VNIR spectroscopy analyses of CM/CI chondrites.

References: [1] Takir D. and Emery J.P. (2010) *DPS* #42, #53.09. [2] Rivkin A.S. et al. (2006) *Icarus*, 185, 563-567. [3] Miliken R.E. and Rivkin A.S. (2009) *Nature Geosci.*, 2, 258-261. [4] Rivkin A.S. et al. (2003) *MPS, 38, 1383-1398*. [5] Jones T.D. et al. (1990) *Icarus*, 88, 172-192. [6] Rivkin A.S. and Emery J.P. (2010) *Nature* 464, 1322-1323. [7] Campins H. et al. (2010) *Nature* 464, 1320. [8] Licandro J. et al. (2011) *A&A* 525, A34. [9] Levison H. et al. (2008) *Icarus*, 196, 258. [10] Grimm R.E. and McSween H.Y. (1989) *Icarus*, 82, 244-280. [11] Rivkin A.S. et al. (2006) *Icarus*, 185, 563-567.

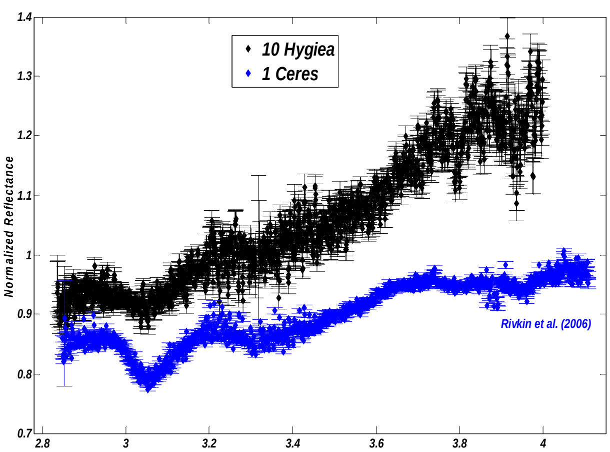

Fig.1. The spectrum of 10 Hygiea (in black) that exhibits quite similar spectrum to 1 Ceres [2] (in blue).

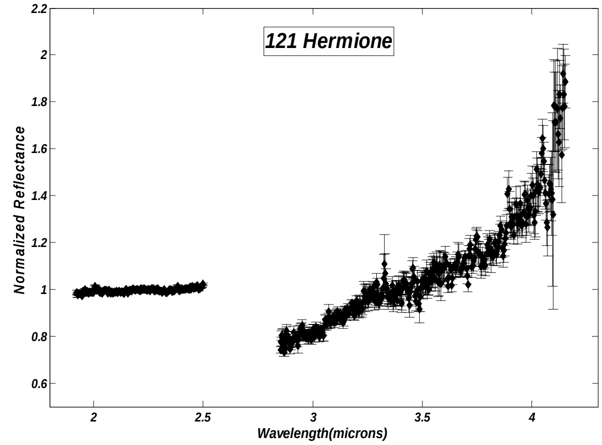

Fig.2. The spectrum of 121 Hermione, showing a sharp OH 3-µm feature with a depth of 20.6±0.7 at 2.95-µm.

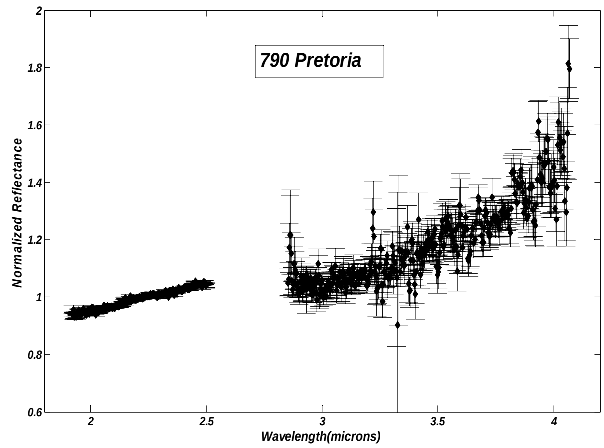

Fig.3. The spectrum of 790 Pretoria, showing a rounded H_2O 3-µm feature with a depth of 8.7±1.2 at 2.95-µm.

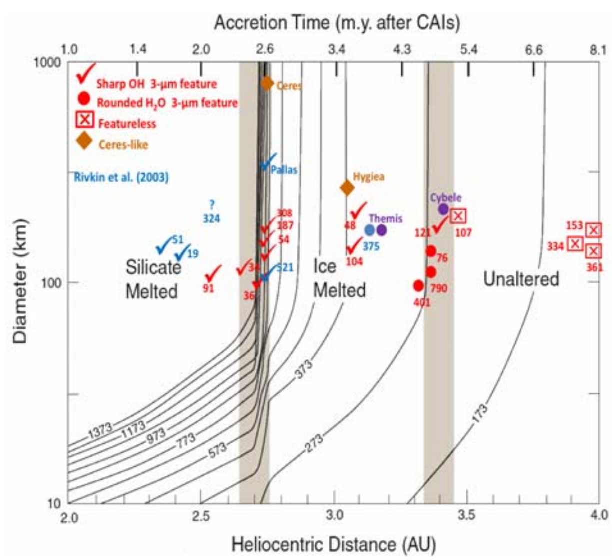

Fig.4. Asteroids analyzed in this study (in red) plus 24 Themis [6, 7], 65 Cybele [8], 1 Ceres [11], and asteroids from [4] are plotted in the thermal model of [10].