HYDRATED MINERALS ON B-CLASS ASTEROIDS . A. S. Rivkin[1], E. S. Howell[2], J. P. Emery[3], and M. Richardson[4], [1]JHU/APL [2]University of Arizona [3]Northern Arizona University [4]Planetary Science Institute

Introduction: We have been studying asteroids (NEAs) in the 2—4-µm region to understand the diversity of their hydrated and hydroxylated minerals, and any correlation between those minerals and visible-near-IR taxonomic class [1]. In previous studies, we found that member of the Ch taxonomic class, marked by the presence of an absorption band at 0.7 µm, have similar 3-µm spectra reminiscent of what is seen in the CM meteorites [2], and that C-complex asteroids > 200 km diameter showed a variety of band shapes suggesting a diversity of hydrated minerals beyond what is seen in the meteorite collection [3]. In this work we turn to the B class, which includes the notable NEAs Bennu and Phaethon, and the main-belt objects Pallas and Themis, among others.

B-class Asteroids: The B-class asteroids in the Bus and Tholen taxonomies are distinguished by decreasing reflectance with increasing wavelength in the 0.5—1.0-µm region [4]. Indeed, the B name was originally a mnemonic for their "blue" spectral slopes. In the Bus taxonomy, the B class is part of the C complex, which includes several other low-albedo asteroid classes, including the large C class that names the complex, and the Cb class, which has spectral properties intermediate to the B and C classes. Measurements to 2.5 µm show members of the B class have a variety of spectral slopes beyond 1 µm, from continued blue slopes to rather red slopes [5,6]. In the latter case, the full 0.5—2.5-µm spectrum shows the shorter-wavelength blue slope to be a shoulder of a wide absorption centered near 1.0—1.2 µm [5,6].

Compositionally, the B class has been associated with carbonaceous chondrite meteorites, as have the other classes in the C complex. The first B-class asteroid to be visited by spacecraft was Bennu, which will also be the first B-class asteroid whose material will be studied on Earth. Work by de León et al. [6] showed that their sample of 45 B-class asteroid spectra could be divided into six different groups, each with a different best-fit meteorite spectral analog, though they also noted that there was basically a continuous distribution of spectral properties in their sample rather than a hiatus between types.

The LMNOP: Since 2001 we have been observing asteroids in the 3-µm region using the SpeX instrument on the NASA IRTF [1-3, 7]. These observations, which we have collectively termed the "L-band Main-belt and NEO Observing Program" (LMNOP), include 15 B-class asteroids. The LMNOP objects also include the Ch-class asteroids and large C-complex asteroids mentioned in the Introduction.

Results: Figure 1 shows 2—4-µm spectra of several representative B-class asteroids in the LMNOP sample, along with Pallas, Bennu (digitized from [8]), and a laboratory spectrum of the CM2 chondrite Cold Bokkeveld [9]. The latter two spectra show obvious qualitative similarity, with deep absorptions centered in the 2.7—2.8-µm region due to phyllosilicate minerals and a roughly linear return to the continuum level at longer wavelengths. While the Pallas spectrum is missing the 2.5—2.8-µm region due to the opacity of Earth's atmosphere, it can be seen that shares those spectral characteristics.

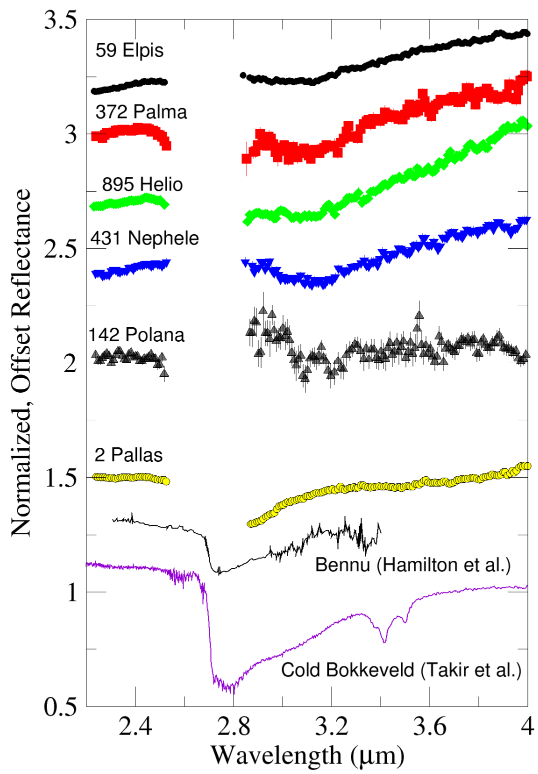

Figure 1: Spectra of selected B-class asteroids from the LMNOP, from Bennu [8] and CM Cold Bokkeveld [9]

The spectra for the other B-class asteroids in Figure 1 also are missing the 2.5—2.8-µm region and are of varying quality, but it is obvious that their spectra are qualitatively different from those of Pallas, Bennu, and Cold Bokkeveld: all show evidence of an absorption bands with centers varying from 3.1—3.2 µm. The B-class asteroid 24 Themis also has such a band, interpreted as ice frost by [10, 11]. In addition, not only the 5 B-class asteroids in Figure 1 have this band shape, but so do all of the 15 B-class asteroids we have observed in the LMNOP save Pallas, 335 Roberta, and on occasion 704 Interamnia.

The ice frost interpretation for Themis and other outer-belt asteroids has been questioned on thermodynamics grounds, with recent work on Rosetta data leading to the suggestion that the band on Themis (and by implication on these asteroids) is instead due to an ammoniated mineral [12]. The fact that these objects are all closer to the Sun than Themis, residing in the middle or even inner asteroid belt, would seem to strengthen the arguments against ice frost being the responsible absorber. On the other hand, ice can persist for long periods at relatively shallow depths in asteroid regolith [13], and it seems at least plausible that a seasonal or diurnal water cycle could exist on these large objects.

Figure 2 is a band depth-band depth plot adapted from earlier papers [3], with position on the plot roughly representing the band shape. Shown are the Cb- and B-class asteroids in the LMNOP sample; objects < 200 km are each represented by a single average of multiple observations if available, while objects > 200 km (and Bennu) are mentioned by name and represented once per observation. Also on the plot are the set of CM chondrites from Takir et al. [9], and three non-B/Cb objects: 51 Nemausa, 1 Ceres, and comet 67P [14], all representing different 3-µm band shapes. To guide the eye, these three objects and 24 Themis all have lines connecting them to the origin. There is also a dashed line showing where the 2.9- and 3.2-µm band depths are equal.

Repeated measurements of Pallas give a sense of variation for a typical single object, but the scatter is parallel to the 1:1 line, and Pallas is well within the area in which the CM meteorites are found. As noted above, the rest of the B-class asteroids other than Roberta and most measurements of Interamnia fall on the other side of the 1:1 line and outside the area of the CM meteorites, as do the Cb asteroids that are also included.

Implications: One of the most obvious implications of this work is that the B-class asteroids are not homogeneous in their hydrated minerals. The phyllosilicates responsible for the 3-µm band on Pallas and Bennu and in CM meteorites are generally not present in amounts sufficient to be important spectral contributors in the other B-class asteroids in the LMNOP sample, no matter what is causing the ~3.1-µm band on those surfaces. It follows that Pallas, at least, is generally unlike the other large B-class asteroids, with the exception of Interamnia and Roberta.

It is not necessarily clear, however, how to best interpret Bennu in light of the variation seen on Interamnia's surface by [3]. Bennu's 3-µm spectrum is clearly unlike that of most of the other B-class asteroids in the LMNOP sample, including 142 Polana, the largest member of a dynamical family Bennu may have been delivered from [15]. Observations of Interamnia include both more Pallas-like and more Themis-like 3-µm bands. It seems possible that on small scales all B-class asteroids could have areas with Bennu/CM-like spectra.

A subject of future work, and a question deserving of more attention is why 3-µm spectra like those seen in most B-class asteroids, and a significant fraction of other low-albedo asteroids, are not seen in the meteorite collection, if it is not due to an unstable absorber like ice frost.

References: [1] Rivkin, A. et al., *ACM 2014*, 448. [2] Rivkin, A. S. et al. (2015) *Astr. J., 150,* 198. [3] Rivkin, A. S. et al. (2019) *JGR, 124,* 1393-1409. [4] Bus, S. J., and Binzel, R. P. (2002) *Icarus, 158,* 146-177. [5] Clark, B. E. et al. (2010) *JGR, 115*. [6] de Leon, J. et al. (2012), *Icarus, 218, 196-206.* [7] Rayner, J. T. et al., *PASP, 115,* 362-382. [8] Hamilton, V. E. et al. (2019), *Nat. Astr., 3,* 332-340. [9] Takir et al. (2013) *Met. Plan. Sci., 48,* 1618-1637. [10] Rivkin, A. S. and Emery, J. P. (2010) *Nature, 464,* 1322-1323. [11] Campins, H. et al. (2010) *Nature, 464,*1320-1321. [12] Poch, O. et al. (2020), *Science, 367.* [13] Schorghofer, N. *Ap. J., 682,* 697. [14] Rousseau, B. et al. (2018), *Icarus, 306,* 306-318. [15] Bottke, W. F. et al. (2015), *Icarus, 247,* 191-217.

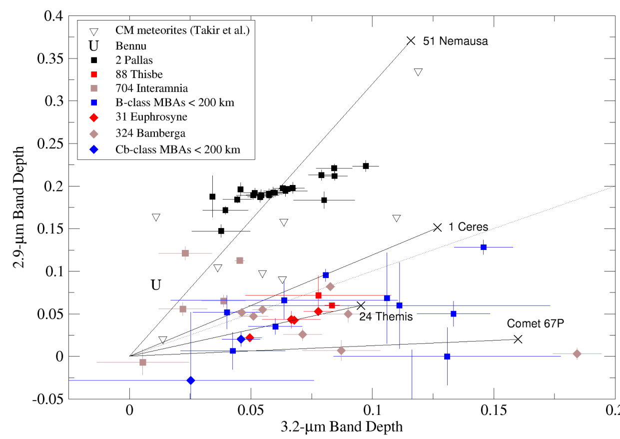

Figure 2: 2.9-µm Band depth – 3.2-µm Band depth plot, representing different band shapes. Pallas and CM meteorites from [9] congregate in one area near the line connecting the Ch asteroid Nemausa to the origin. Bennu [8] follows the same trend. Most B asteroids and the related Cb asteroids are found in a different region, where meteorite spectra are absent.