THE L-BAND MAIN-BELT AND NEO OBSERVING PROGRAM (LMNOP): SOME FINAL RESULTS FROM PHASE 1 A. S. Rivkin[1], J. P. Emery[2], and E. S. Howell[3] [1]JHU/APL (andy.rivkin@jhuapl.edu), [2]University of Tennessee, [3]University of Arizona

Introduction: Since 2002 we have been using the SpeX instrument on the NASA Infrared Telescope Facility (IRTF) [1] to study asteroids in the 3-µm spectral region, which contains absorption bands diagnostic of water and hydroxyl. The dataset has led to several papers on individual objects like Ceres, Vesta, Lutetia, 1996 FG3, and others [2-6]. The upgrading of Spex in 2014 has provided a convenient time to analyze the dataset as a whole, which we refer to as the L-band Main-belt and NEO Observing Program (LMNOP). While the LMNOP is a collection of projects rather than a survey per se, the consistent data collection and reduction techniques allow us to treat the data as though it were collected as a survey.

Survey Data: In all, data was taken on 87 nights during the first phase of the LMNOP with the original SpeX, with 390 observtions of 214 different asteroids. C-complex asteroids were the majority of targets (112 objects), and were nearly a majority of observations (181). A total of 43 observations of 36 Ch or Cgh asteroids were made. It was found that basically all of the Ch/Cgh asteroids shared a common spectral shape (called "Pallas type" or "sharp type" in the literature), as detailed in a recently-published paper [7].

An additional 156 observations of 83 C-complex asteroids were made beyond those of Ch asteroids. Eleven asteroids classified in the P class by Tholen are also included (note some Bus-DeMeo classifications may differ), along with several low-albedo X-complex asteroids. The remainder of the observations were of higher-albedo (S-complex, Tholen M-class, etc.) asteroid, which will be described in work to follow this.

Band Shapes: Several workers have identified different band shapes in the 3-µm region (Figure 1), with one scheme using type asteroids [8] ("Ceres-type", "Pallas-type", "Themis-type", "Nysa type") and another mixing type asteroids with shape descriptions ("sharp-type", "rounded-type", "Ceres-type", "Europa-type") [9]. While a formal taxonomy is still being developed by the community, we see great diversity in the LMNOP sample, including objects with spectral shapes that appear intermediate between types and objects that seem to have differing spectral shapes at different apparitions (Figure 2). Here and below, we classify objects based on inspection of spectra pending a more quantitative means of separating the Ceres types from the Themis types.

Several objects are seen with band shapes like Ceres, as has been previously noted by others [8-10]. While the composition that is represented by this spectral shape is still a matter of some debate [11,12], it is likely that this same composition is present beyond Ceres, and similarly that other objects must have shared similar conditions to those under which Ceres' surface composition was created.

The Ceres-type spectra that have been identified so far are all on members of the C complex. The smallest possible Ceres-type, 47 Aglaja, is 127 km in diameter. Higher-quality spectra of 10 Hygiea shows some very close matches to Ceres over the entire 0.8-4 µm region, other than a difference in spectral slope.

The "Themis types" as defined here include objects with a wide range of band centers, from 3.1-3.2 µm. Indeed, some objects appear to be qualitative matches to VIRTIS spectra of 67P [13], which have a band at 3.2 µm thought to be due to organic materials, though not (yet?) assigned to specific minerals (Figure 3).

Correlation with Bus/Tholen Taxonomy: No correlation as strong as that between Ch asteroids and Pallas-type bands is seen among other classes, which have at least some variety in 3-µm band shape. Of the 29 observations of B-class asteroids for which a band shape can be assigned with any confidence, 14 have Pallas type bands. However, 10 of those 14 observations are of Pallas itself. Of the remaining observations, 11 show Themis-type bands, representing 8 different asteroids. There are 42 observations of C-class, Cb-class, and Cg-class asteroids for which band shapes can be assigned, 15 of which are Pallas-type, 27 of which are Ceres or Themis type (representing 13 and 12 different asteroids, respectively). When looking at the 15 observations of 7 Tholen P-class asteroids in the sample, only one (of 790 Pretoria) is consistent with a Pallas-type spectrum, with the rest appearing Themis-type. Table 1 summarizes the distribution of 3-µm band shapes among the low albedo classes.

Variation in Asteroid Spectra?: A surprise in the LMNOP dataset is some amount of variation between apparitions for some targets. Because the 3-µm region is particularly sensitive to the precipitable water content of the atmosphere and many of the targets are faint, some amount of variation may be ascribed to observational uncertainty. However, variation can be seen even in some bright, well-observed targets. While Pallas shows a consistent band shape with only minor variations in band depth, spectra of 10 Hygiea and 704 Interamnia can be found that appear very Ceres-like or as intermediate between Ceres- and Pallas-type.

Final Thoughts: The LMNOP is by far the largest dataset for studying the 3-µm spectral behavior of asteroids. Asteroids show variety in spectral shapes in this wavelength region not dissimilar to the variety seen at shorter wavelengths, and for low albedo asteroids the 3-µm region provides the best opportunities for remote sensing of composition. We will discuss the findings mentioned above as well as additional conclusions.

References: [1] Rayner J. T. et al. (2003) *PASP, 115*, 362–382. [2] Rivkin A. S. et al. (2006) *Icarus, 180*, 464–472. [3] Rivkin A. S. and Volquardsen, E. L. (2010) *Icarus, 206*, 327–333. [4] Rivkin A. S. et al. (2011) *Icarus, 216*, 62–68. [5] Rivkin A. S. et al. (2013) *Icarus, 223*, 493–498. [6] Rivkin A. S. et al.. (2015) in *Asteroids* IV, U. Arizona Press, Tucson. [7] Rivkin A. S. (2015) *Astronomical Journal, 150*, 198. [8] Rivkin, A. S. (2010) *Bulletin of the American Astronomical Society*, *42,* abstract #1073. [9] Takir D. and Emery, J. (2012) *Icarus, 219*, 641–654. [10] Rivkin A. S. et al. (2011) *EPSC-DPS Joint Meeting 2011*, page 1271. [11] Milliken R. E. and Rivkin A. S. (2009) *Nature Geoscience*, *2*, 258–261. [12] De Sanctis M. et al. (2015), *Nature*, *528*, 241–244. [13] Capaccioni F. et al. (2015), *Science, 347,* 6220-6223.

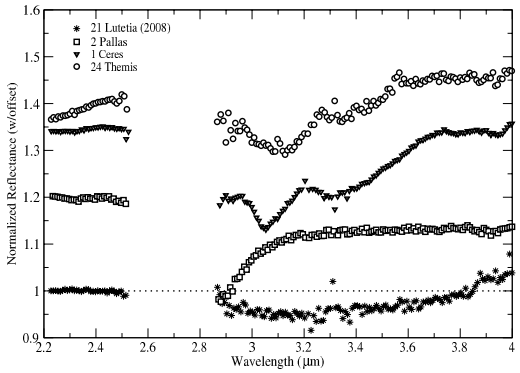

Figure 1: A variety of band shapes in the 3-µm region has been seen on asteroids. This figure from [6] shows the major spectral shapes that have been identified so far.

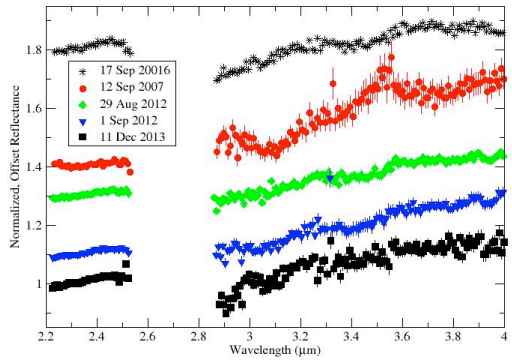

Figure 2: 704 Interamnia has been observed several times in the LMNOP. It appears to have spectra that appear more Pallas-like on occasion, and intermediate to Ceres-type on other occasions (2007, Sep 2012). These differences, if repeatable, are likely due to regional differences on Interamnia.

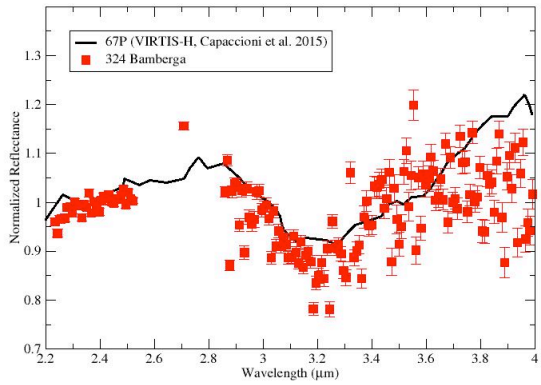

Figure 3: The VIRTIS spectra of 67P show an absorption band near 3.2 µm they attribute to organic materials [13]. At least some of the asteroids in the LMNOP show a similar spectral feature. At the present they are classified as Themis-type objects, but additional work on classification schemes may split them into additional classes.

Taxon	Number of Observations	Number of Pallas types	Number Themis/Ceres types
All low alb	220	70	52
Ch/Cgh	43	40	0
B	43	14	11
C/Cg/Cb	61	15	27
Tholen P	39	1	14

Table 1: 3-µm band shapes in taxonomic subgroups. Note that the two rightmost columns do not add up to the second column because not every observation has been classified at this point.