Hungaria Asteroid Region Telescopic Spectral Survey (HARTSS) I: Stony Asteroids Abundant in the Hungaria Background Population

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Abstract

The Hungaria asteroids remain as survivors of late giant planet migration that destabilized a now extinct inner portion of the primordial asteroid belt and left in its wake the current resonance structure of the **Main Belt**. In this scenario, the Hungaria region represents a “purgatory” for the closest, preserved samples of the asteroidal material from which the terrestrial planets accreted. Deciphering the surface composition of these unique samples may provide constraints on the nature of the primordial building blocks of the terrestrial planets. We have undertaken an observational campaign entitled the Hungaria Asteroid Region Telescopic Spectral Survey (HARTSS) to record near-infrared (NIR) reflectance spectra **in order** to characterize their taxonomy, surface mineralogy, and potential meteorite analogs. **The overall objective of HARTSS is to evaluate the compositional diversity of asteroids located throughout the Hungaria region. This region harbors a collisional family of Xe-type asteroids, which are situated among a background (i.e., non-family) of predominantly S-complex asteroids. In order to assess the compositional diversity of the Hungaria region, we have targeted background objects during Phase I of HARTSS. Collisional family members likely reflect the composition of one original homogeneous parent body, so we have largely avoided them in this phase.** We have employed NIR instruments at two ground-based telescope facilities: the NASA Infrared Telescope Facility (IRTF), and the Telescopio Nazionale Galileo (TNG). Our data set includes the NIR spectra of 42 Hungaria asteroids (36 background; 6 family), of which 27 were observed during HARTSS (22 at IRTF, 5 at TNG). To complement our data set, we have **included previously published NIR spectra of 15 objects**, and **previously published** visible (VIS) spectra of 21 asteroids. We find that stony S-complex asteroids dominate the Hungaria background population (29/36 objects; ~80%). C-complex asteroids are uncommon (2/42; ~5%) within the Hungaria region. Background S-complex objects exhibit considerable spectral diversity as band parameter measurements of diagnostic absorption features near 1- and 2- μm **indicate** that several different S-subtypes are represented therein, which translates to a variety of surface compositions. We identify the Gaffey S-subtype (**Gaffey et al. [1993]. *Icarus* 106, 573-602**) and potential meteorite analogs for 24 of these S-complex background asteroids. Additionally, we estimate the olivine and orthopyroxene mineralogy for 18 of these objects using spectral band parameter analysis established from laboratory-based

studies of ordinary chondrite meteorites. **Nine of the asteroids have band parameters that are not consistent with ordinary chondrites. We compared these to the band parameters measured from laboratory VIS+NIR spectra of six primitive achondrite (acapulcoite-lodranite) meteorites.** These comparisons suggest that two main meteorite groups are represented among the Hungaria background asteroids: unmelted, nebular *L*- (and possibly *LL*-ordinary chondrites), and partially-melted primitive achondrites of the acapulcoite-lodranite meteorite clan. **Our results** suggest a source region for *L* chondrite like material from within the Hungaria region, with delivery to Earth via leakage from the inner boundary of the Hungaria region. *H* chondrite like mineralogies appear to be absent from the Hungaria background asteroids. **We therefore** we conclude that the Hungaria region is not a source region for *H* chondrite meteorites. Seven Hungaria background asteroids have spectral band parameters consistent with partially-melted primitive achondrites, but the probable source region of the acapulcoite-lodranite parent body remains inconclusive. **If the proposed connection with the Hungaria family to fully-melted enstatite achondrite meteorites (i.e., aubrites) is accurate (Gaffey et al. [1992]. *Icarus* 100, 95-109; Kelley and Gaffey [2002]. *Meteorit. Planet. Sci.* 37, 1815-1827), then asteroids in the Hungaria region exhibit a full range of petrologic evolution: from nebular, unmelted ordinary chondrites, through partially-melted primitive achondrites, to fully-melted igneous aubrite meteorites.**

1. Introduction

The Hungaria asteroids are unique among the minor planets. These “neighbors” of the terrestrial planets reside interior to the **Main Belt** of asteroids by at least 0.1 AU, are highly-inclined to the ecliptic, and may have occupied their current location since early in Solar System history (Warner et al., 2009; Milani et al., 2010; Bottke et al., 2012). Mars-crossing and near-Earth asteroids (NEAs) can wander even closer to the terrestrial planets, but those objects are dynamically short-lived (~ 10 Myr) escapees from the **Main Belt** (Morbidelli et al., 2002; Binzel et al., 2004a). **In contrast, the Hungaria region is a quasi-stable orbital space bound by mean-motion and secular resonances (Carvano et al., 2001; Warner et al., 2009; Milani et al., 2010; McEachern et al., 2010) (Figure 1). Hence, asteroids entering this region have dynamic half-lives from ~ 100 million years (Myr) (Migliorini et al., 1998; McEachern et al., 2010) to about one billion years (Gyr) (Milani et al., 2010).** It is therefore likely that many asteroids in the Hungaria region have resided there since the giant planets completed their migration to their current orbits (Warner et al., 2009; Bottke et al., 2012). Nevertheless, there is some leakage from the inner-edge of the Hungaria region, which helps to replenish the short-lived Mars-crossing population (Migliorini et al., 1998; Michel et al., 2000; Milani et al., 2010; Ćuk et al., 2014) and vice-versa (McEachern et al., 2010), thereby providing a pathway for meteoroids to reach the Earth from the Hungaria region (Gaffey et al., 1992; Ćuk et al., 2014).

The Hungaria region contains $\sim 14,000$ known, small ($D < 11$ km) asteroids (JPL Horizons¹) that populate orbital space roughly defined by; $1.78 < a < 2.0$ AU, $e < 0.18$, and $16^\circ < i < 34^\circ$ (Warner et al., 2009). This region is inhabited by the Hungaria collisional family (PDS² ID 003) of mainly Xe-type asteroids, which comprises a significant fraction of the total population in the region (Carvano et al., 2001; Assandri and Gil-Hutton, 2008; Warner et al., 2009; DeMeo and Carry, 2013). Collisional families originate from the disruption of a common parent body (Zappalà et al., 2002; Cellino et al., 2009; Nesvorný et al., 2015), and share tightly-clustered proper orbital elements (Hirayama, 1918; Zappalà et al., 1990; Zappalà et al., 1994; Zappalà et al., 1995). The collision that fragmented the Hungaria parent body occurred approximately 275 Myr (Milani et al., 2010) to 500 Myr (Warner et al., 2009) ago, forming the Hungaria family

¹ JPL Horizons, accessed March 3rd, 2016: http://ssd.jpl.nasa.gov/sbdb_query.cgi

² Planetary Data System Small Bodies Orbital Data: <http://sbn.psi.edu/pds/archive/orbital.html>

with family namesake 434 Hungaria the presumed largest existing fragment. This family is situated among a background (i.e., non-family members) of predominantly S-complex asteroids (Carvano et al., 2001; Warner et al., 2009).

Color and spectral observations of asteroids have revealed a broad compositional gradient among the larger asteroids ($D > \sim 20$ km) in the **Main Belt** (Gradie and Tedesco, 1982; Bus, 1999; DeMeo and Carry, 2013; DeMeo and Carry, 2014). C-complex objects, believed to represent the primitive carbonaceous chondrite meteorites, are most abundant in the outer-belt, while S-complex asteroids, believed to represent nebular (chondritic) or igneous (achondritic) stony-meteorites, dominate the inner-belt (Gradie and Tedesco, 1982; Mothé-Diniz et al. 2003; DeMeo and Carry, 2013; DeMeo and Carry, 2014). **Extending this trend further, the degree of igneous differentiation experienced by asteroids interior to the Main Belt and in the terrestrial planet region is also of interest. The feeding zones for the accretion of terrestrial planets can be relatively narrow, incorporating very little material from beyond 2 AU in some planetary accretion models (Raymond et al., 2009). Therefore the terrestrial planets most likely accreted from nearby planetary embryos and planetesimals, not from material in the Main Belt.** However, the evidence for this process has been lost as planetesimals in the inner portion of the protoplanetary disk (PPD) where the terrestrial planets formed were either accreted by planetary embryos or scattered out of the inner PPD early in solar system history (Weidenschilling et al., 1997; Bottke et al., 2006a; Kleine et al., 2009). Bottke et al. (2012) has suggested that the present Hungaria asteroids remain as high-inclination survivors of late giant planet migration that destabilized a now extinct inner portion of the primordial asteroid belt (“E-belt”) and left in its wake the current resonance structure of the **Main Belt** (Morbidelli et al., 2010; Minton and Malhotra, 2011). This E-belt may have extended inward as far as 1.7 AU, much nearer to the terrestrial planets than the current **Main Belt**. Therefore, we argue that the Hungaria region represents a “purgatory” for preserved, *in situ* samples of the asteroidal material from which the terrestrial planets accreted. Deciphering the surface mineralogy and establishing asteroid-meteorite connections for Hungaria asteroids may then provide fundamental constraints on the composition(s) of the primordial building blocks of the terrestrial planets.

The spectral and chemical properties of terrestrial and extraterrestrial minerals analyzed in the laboratory, compared with **ground-based telescopic near-infrared (NIR) spectral observations**, can constrain asteroid surface mineralogy and provide evidence for the

establishment of asteroid-meteorite connections. This is practicable because NIR spectra of S-complex and several end-member asteroid types (DeMeo et al., 2009) that are rich in **the** mafic silicate minerals olivine and pyroxene carry strong 1- and/or 2- μ m absorption band features (Band I and II, respectively). Cloutis et al. (1986) used laboratory spectra of natural terrestrial olivine and orthopyroxene mixtures to demonstrate that band parameters (i.e., band center, depth, area, and ratio of band areas) of the 1- and 2- μ m bands can be used as a gauge of olivine and orthopyroxene modal abundance and chemistry. In particular, Cloutis et al. (1986) found that the Band Area Ratio (BAR - Band II area divided by Band I area) is a sensitive indicator of the olivine to orthopyroxene abundance and that BAR exhibits sufficient insensitivity to mineral chemistry and grain size that reasonable estimates of modal abundances can be formed. Cloutis et al. (1986) also showed that Band I center is responsive to both mineral abundance and chemistry so that the Band I center position can be used to determine the molar Fe^{2+} contents of olivine and orthopyroxene mineral phases. Utilizing these relationships, telescopic spectra can be analyzed to infer asteroid surface mineralogy and potential meteorite analogs.

From the broad compositional gradient observed in the Main Belt, it is argued that bodies of a given size located in the inner portion of the primordial asteroid belt experienced higher peak temperatures than similar sized bodies in the outer belt (McSween et al., 2002). Therefore, we hypothesize that planetesimals in the inner-most part of the primordial asteroid belt underwent partial- to full-melting and differentiation. The dynamical scenario suggested by the E-belt model implies that the present Hungaria asteroids sample material that originated in the inner-most portion of the primordial asteroid belt. Consequently, the Hungaria region should retain at least some of the petrologically-evolved material that formed there. Primitive achondrite meteorites of the acapulcoite-lodranite clan demonstrate that partially-melted asteroids exist and therefore provide a basis for spectral comparison. We test this hypothesis by analyzing NIR spectra of 42 Hungaria asteroids (36 background; 6 family) and by performing detailed spectral band parameter analyses for 24 S-complex background asteroids and for spectra of six primitive achondrite meteorites obtained from the Keck/NASA Reflectance Experiment Laboratory (RELAB) database. The spectra reported herein represent initial results from a larger NIR observational campaign of Hungaria asteroids entitled Hungaria Asteroid Region Telescopic Spectral Survey (HARTSS). The overall objective of HARTSS is to record the NIR reflectance

spectra of Hungaria asteroids with absolute magnitude (H_V) <16 to **evaluate** their surface mineralogy and compositional diversity through taxonomic classification and spectral band parameter measurements.

2. HARTSS Observations and Data Reduction

HARTSS is an on-going observational campaign that commenced in 2009 September. **As of 2013 November**, we **had** obtained telescopic near-infrared (NIR) reflectance spectra of 42 Hungaria region asteroids (**36 background; 6 family**). We have employed NIR instruments at two separate facilities: the SpeX spectrograph (Rayner et al., 2003) on NASA’s 3.0 m Infrared Telescope Facility (IRTF) at Mauna Kea, Hawai’i, and the Near-Infrared Camera and Spectrometer (NICS) on the 3.6 m Telescopio Nazionale Galileo (TNG) at El Roque de Los Muchachos Observatory, San Miguel de La Palma, Canary Islands, Spain (Oliva 2000; Baffa et al., 2001). Observational circumstances are provided in Table 1. Stars with solar-like spectral type, B-V color, and V-K color were selected as solar analog standards (Table 1). Data regarding these standard stars were obtained from the SIMBAD database³ (and references therein).

2.1. IRTF SpeX Near-Infrared Spectra

HARTSS includes 22 Hungaria asteroids observed with IRTF SpeX (0.7-2.5 μm) over eight different nights spanning 2009 September to 2013 November (Table 1). The spectra were recorded using SpeX in the low-resolution prism mode **without the dichroic and using** a 0.8” x 15” slit, in which the entire wavelength range is dispersed in a single order with an average resolving power over the whole spectral range of $R \sim 75$. The telescope was nodded in a standard ABBA sequence, with the target dithered 7.5” along the slit. The slit was kept aligned with the parallactic angle ($\pm 10^\circ$) to minimize the effects of differential refraction across the wavelength range. On-chip integration times (t_{int}) were held to a maximum of 120 s due to variability of atmospheric emission (mainly OH⁻ line emission). Distinct local solar standard stars were observed for each target asteroid. Care was taken to closely match local solar standard and asteroid observations both temporally and spatially. Accordingly, local solar standards were

³ <http://simbad.u-strasbg.fr/simbad/>

located within $\sim 3^\circ$ of the target and asteroid observations were bracketed close in time (~ 25 min) by local solar standard observations (Emery et al., 2011). Typically, at least eight local solar standard integrations were collected for each ABBA asteroid sequence.

Reduction of the spectral data was performed using the custom IDL (Interactive Data Language) routine Spextool (Cushing et al., 2004). This routine enables the extraction and calibration of SpeX data, including subtraction of dithered A-B pairs to remove background sky emission, division by a master flat-field to remove pixel-to-pixel variations across the chip, and extraction from two-dimensional spectral images to one-dimensional spectra (see Emery and Brown, 2003). A calibration box attached to SpeX contains an integrating sphere that is illuminated for flat-field frames and an Ar lamp for wavelength calibration (Rayner et al., 2003). **Reflectance values for each asteroid were calculated by dividing the asteroid spectrum by the corresponding local solar standard spectrum. The spectrum is corrected for atmospheric telluric absorptions and the solar spectrum during this process.** Multiple integrations of the divided asteroid spectra were then summed within Spextool to increase the signal-to-noise (S/N) ratio. This process typically yielded an S/N ratio >100 for the majority of the final asteroid spectra.

We supplement our dataset with 15 additional NIR spectra also obtained with IRTF SpeX from the following sources (see Table 1): data from the MIT-UH-IRTF Joint Campaign for NEO Reconnaissance⁴ (Binzel et al., 2006) (asteroids 2074, 2449, 3635, 3873, 5577, 5641, and 6249); data from Lindsay et al., 2015 (asteroids 2577, 3309, 4674, and 5905); data from Clark et al., 2004 (asteroids 434, 1103, and 2048); and data from Binzel et al., 2004b (asteroid 4142).

[Table 1 – Observing Parameters]

2.2. TNG NICS Near-Infrared Spectra

HARTSS includes five Hungaria asteroids observed with NICS (0.8-2.4 μm) at TNG on the night of 2013 October 31 (Table 1). The NIR spectra were recorded using the high-throughput NICS in low-resolution mode utilizing an Amici prism disperser (Oliva, 2000; Baffa et al., 2001). All spectroscopic modes use the Large-Field camera, which has a plate scale of

⁴ <http://smass.mit.edu/minus.html>

0.25"/pixel. We used the 1.5" width slit, corresponding to a spectral resolving power of $R=34$, quasi-constant along the spectra. The slit was kept aligned with the parallactic angle ($\pm 10^\circ$) to minimize the effects of differential refraction across the wavelength range. Several images through the Js filter were acquired to identify the asteroid in the field-of-view and to orient the slit. The acquisition of data consisted of 90 s integrations in two different positions in the slit by nodding the telescope by 10" (i.e., positions A and B). Multiple ABBA sequences were acquired to increase the S/N. The total integration time varied depending on the visual magnitude of the target (Table 1) and on weather conditions.

Sky conditions were poor during the night of 2013 October 31, showing wide fluctuations in seeing, wind, and cloud coverage conditions. These conditions result in the variable quality of both asteroid and solar analog standard spectra without direct correlation to brightness or airmass. Furthermore, due to sky transparency fluctuations, telluric corrections near strong atmospheric absorptions (1.32-1.46; 1.77-1.95 μm) can be poor for these objects (see Appendix A.1). Spectroscopic data reduction utilized standard Image Reduction and Analysis Facility (IRAF) tasks (see Licandro et al., 2001; Pinilla-Alonso et al., 2016). These tasks include flat-field corrections, sky background removal, and extraction of 1-dimensional spectra. Wavelength calibrations were performed on consecutive AB pairs using a look-up table based on the theoretical dispersion predicted by ray-tracing and adjusted to best-fit the observed spectra of calibration sources and telluric absorptions. To obtain relative reflectance and to correct for telluric absorptions, each AB asteroid pair was divided by the spectra of several G-stars (Landolt, 1992) that have proved to be suitable solar analog standards (de León et al., 2010). Subpixel offsetting was applied during solar analog standard star division to correct for errors in wavelength calibrations due to instrumental flexures. Individual relative reflectances obtained for each asteroid relative to the different solar analog standards were averaged to derive final relative reflectances.

3. Results

3.1. Combined Visible and Near-Infrared Spectra

We combined available published visible (VIS) spectral data ($\sim 0.4\text{-}0.9\ \mu\text{m}$) with our NIR spectral data in order to provide more robust taxonomic classifications and mineralogical interpretations for our surveyed Hungaria asteroids. Overall, we supplemented 21 of 42 Hungaria asteroids in our NIR dataset with VIS spectral data from several sources (see Appendix A.1). A scaling factor was used to fit the NIR reflectance data to the normalized VIS reflectances in the wavelength region between $0.70\text{-}0.80\ \mu\text{m}$, and NIR reflectance errors are also multiplied by the same scaling factor. The final VIS+NIR spectra are normalized to unity at $0.55\ \mu\text{m}$, while final NIR spectra are normalized at $1.25\ \mu\text{m}$. We present all 42 NIR and VIS+NIR Hungaria asteroid spectra (**36 background; 6 family**) in Figure A1.

3.2. Taxonomic Classification

The taxonomic classifications of our asteroid reflectance spectra were determined using the taxonomic system of Bus-DeMeo (DeMeo et al., 2009). This taxonomy builds upon the earlier visible-**wavelength** Bus taxonomy (Bus, 1999; Bus and Binzel, 2002) by extending the wavelength coverage of asteroid reflectance spectra into the NIR. The Bus-DeMeo taxonomic system is constructed through principal component analysis **based on spectral shape (albedo is not considered)** and separates asteroid reflectance spectra into 25 different spectral types within four main complexes: S-complex (S, Sa, Sq, Sr, and Sv), C-complex (B, C, Cb, Cg, Cgh, and Ch), X-complex (X, Xc, Xe, Xk, and Xn), and End Members (D, K, L, T, A, O, Q, R, and V). We identified the taxonomic type of each of our 42 Hungarias using MIT's Bus-DeMeo Taxonomy Classification Tool⁵; the results are presented in Table 2. For our VIS+NIR spectra the Bus-DeMeo principal component analysis arrives at a unique taxonomic classification for most spectra (15 of 21). For the 21 spectra with **NIR-only data** the Bus-DeMeo classification is non-unique, and we report the spectral types with the two lowest absolute residuals (Table 2). S-

⁵ <http://smass.mit.edu/busdemeoclass.html>

complex asteroids display widely varying spectral slopes, and the Bus-DeMeo classification notates high-slope (at an arbitrary cut-off of 0.25) objects with a “w” moniker.

Figure 2 shows the Bus-DeMeo taxonomic complexes (S-, X-, and C-complex) for our sample of 42 Hungaria asteroids. We plotted H_v versus the proper semi-major axis of ~ 3800 Hungarias ($H_v \leq 18.0$) that are defined as members of the family population (Knežević et al., 2002; Bottke and Nesvorný, *personal comm.*). We then plotted **all remaining** numbered asteroids **with $H_v \leq 18.0$ (~ 2300)** in the Hungaria region⁶ **to show the background population**. The thermal forces of the Yarkovsky/YORP effect spread the fragments of a collisional family primarily in semi-major axis (see Bottke et al., 2002a; Bottke et al., 2006b; Nesvorný et al., 2015). **We have delineated the Hungaria family “Yarkovsky curves” (Figure 2)**, which create a size-dependent V-shaped envelope around the center of the family, **as in Warner et al. (2009)**. The taxonomic distribution within the Hungaria region shown in Figure 2 indicates a spectrally diverse Hungaria background population prevalent in S-complex asteroids (29 of 36 objects; $\sim 80\%$). The taxonomic distribution among Hungaria family members shows that three of five smaller fragments observed during HARTSS are consistent with the Xe-type taxonomy of the largest collisional fragment 434 Hungaria (Table 2). C-complex asteroids are uncommon (2 of 42 objects; $\sim 5\%$) within the Hungaria region (Figure 2). It is important to recognize that asteroid taxonomic classifications represent spectral groups, which are not necessarily equivalent to asteroid surface compositions (Gaffey, 2010). To establish more robust compositional inferences, asteroid reflectance spectra can be analyzed for spectral band parameters to derive mineralogical information and to identify potential meteorite analogs for S-complex objects (§ 4. below).

[Table 2 – Hungaria Physical Properties and Taxonomy]

4. Spectral Analysis

Initial calibrations useful for the correlation of asteroid surface mineralogy were developed by obtaining laboratory spectra of natural terrestrial olivine and pyroxene mixtures (Adams, 1974; Cloutis et al., 1986; King and Ridley, 1987). More recent studies have utilized the

⁶ JPL Horizons, accessed March 3rd, 2016: http://ssd.jpl.nasa.gov/sbdb_query.cgi

chemical and spectral analyses of stony-meteorite samples to develop mineralogic calibrations (Burbine et al., 2009; Dunn et al., 2010a; Dunn et al., 2010b; Sanchez et al., 2014). These calibrations are useful for estimating the mineral chemistry and modal abundance of mafic silicate minerals on asteroid surfaces through band parameter analyses of their reflectance spectra. Accordingly, we analyzed the band parameters of NIR and VIS+NIR spectra from a subset ($n = 24$) of the S-complex asteroids in our study for clues to their surface mineralogy, and to establish asteroid-meteorite connections between Hungaria background asteroids and analogous meteorite groups. Spectra from five S-complex asteroids in our sample: 5175 Ables, 6310 Jankonke, 7173 Sepkoski, 7187 Isobe, and 9873 1992 GH (see Figure A1), are too noisy, or have insufficient Band I or Band II depths for useful mineralogical analysis and are not considered further.

4.1. Band Parameter Analysis

We measured spectral band parameters (Band I and II centers, depths, areas, and BARs) with a new freely-available IDL-based algorithm, the Spectral Analysis Routine for Asteroids or SARA⁷ (Lindsay et al., 2015). This routine divides the absorption bands by a straight-line continuum by fitting 5th order polynomials to absorption band shoulders and fitting the linear continuum tangentially to the shoulders. Band centers and depths are measured three times using 3rd through 5th order polynomial fits to the lower one-half of Band I and to the entirety of Band II. The averages of the three polynomial fits are adopted as the final values. BAR is calculated as (Band II area)/(Band I area). Errors are computed using a Monte-Carlo method, which produces 20,000 synthetic data measurements for each polynomial order, yielding $3 \times 20,000$ measurements to derive band centers and depths. The final 1σ center and depth errors are defined as the average of the three error measurements. For a detailed treatment regarding SARA see Lindsay et al. (2015). The band parameter results for the 24 S-complex Hungaria background asteroids are presented in Table 3. For comparison of the asteroid band parameter data to potential meteorite analogs for which no mineralogic calibrations have been determined, we used SARA to measure the band parameters from VIS+NIR spectra of six primitive achondrite

⁷ SARA is freely available via GitHub: <https://github.com/SeanSLindsay/SARA.git>.

(acapulcoite and lodranite) meteorites (Table 4; see § 4.2.2). These meteorite spectra were obtained from the RELAB spectral database⁸.

4.1.1. Band Parameter Temperature Corrections

Hungaria asteroid equilibrium surface temperatures vary with albedo and distance from the Sun, but are generally about 200 K (see Table 3). The surface temperature of an asteroid will affect Band I and Band II positions and widths because band centers move to shorter wavelengths as the temperature of the surface decreases (Singer and Roush, 1985; Roush and Singer, 1987; Lucey and Keil, 1998; Hinrichs et al., 1999; Schade and Wäsch, 1999; Moroz et al., 2000; Hinrichs and Lucey, 2002; Sanchez et al., 2012). Laboratory spectra of possible meteorite analogs are typically measured at room temperature (~300 K), so band parameters measured from telescopic spectra of Hungaria asteroids are not directly comparable to laboratory generated spectral data. As a result, temperature corrections to our asteroid band parameters are necessary before comparisons are made to laboratory-derived measurements or calibrations. The equilibrium surface temperature (T_{eq}) in Kelvin of an asteroid can be estimated in the fast-rotator approximation from the following equation:

$$T_{eq} = [L_{\odot}(1 - A)/16\pi\eta\epsilon\sigma r^2]^{1/4} \quad (1)$$

where $L_{\odot}$ is the Solar luminosity (3.828×10^{26} W), A is the bolometric Bond albedo of the asteroid, η is the beaming factor (assumed to be unity), ϵ is the infrared emissivity of the asteroid (assumed to be 0.9), σ is the Stefan-Boltzmann constant, and r is the heliocentric distance of the asteroid at the time of observation. We use the fast-rotator approximation as a reasonable estimate of the average daytime temperature on the surfaces, even though we expect the actual temperature distribution to be quite different from this approximation. For our sample of Hungaria asteroids, we compute Bond albedos by multiplying visible geometric albedos from IRAS (Tedesco et al., 2002) by a phase integral of 0.39. If an IRAS albedo does not exist for an asteroid, we use the average visible geometric albedo from DeMeo and Carry (2013; see their Table 4) that is representative of the taxonomic classification of the asteroid. Sanchez et al.

⁸ http://www.planetary.brown.edu/relabdocs/relab_disclaimer.htm

(2012) found that temperature effects for Band I center are negligible; the Band II absorption feature is most affected by temperature variations. Accordingly, we correct our Band II centers and BARs with the following linear corrections derived for these effects with respect to room temperature Sanchez et al. (2012):

$$\Delta BIIC (\mu m) = 0.06 - 0.0002 \times T (K) \quad (2)$$

$$\Delta BAR = 0.00075 \times T (K) - 0.23 \quad (3)$$

These corrections are added to the measured Band II centers and BARs for each asteroid in order for these data to be compared to laboratory-derived spectral data. The calculated equilibrium temperatures and temperature corrected values for Band II center and BAR ($BIIC_{tcorr}$ and BAR_{tcorr}) for each S-complex asteroid is listed in Table 3.

[Table 3 – Band Parameter Analysis for Hungaria Asteroids]

4.2. Asteroid S-subtypes and Asteroid-Meteorite Connections

Because spectral band parameter analysis includes division of the absorption bands by a straight-line continuum, band parameters such as Band centers and BARs are insensitive to continuum slope variations and effectively “see through” space weathering processes (Cloutis et al., 1986; Gaffey et al., 2002; Gaffey, 2010). Gaffey et al. (1993) characterized the spectral band parameters of S-complex asteroids, separating the complex into seven subtypes, S(I-VII), that provide approximate mineralogic interpretations and possible meteorite analogs within Band I center versus BAR space. **These seven subtypes exhibit a range of compositions: from nearly pure olivine [S(I)], olivine (ol) + orthopyroxene (opx) mixtures [S(II)-S(VI)], nearly pure pyroxene/pyroxene-feldspar-metal mixtures [S(VII)], to basaltic achondrite compositions [BA].** The Band I centers and BARs for our 24 Hungaria background S-complex asteroids are shown in Figure 3a. The majority of the asteroids cluster near the ol+opx mixing line of Cloutis et al. (1986), suggesting that our sample of S-complex asteroids **are composed of an** essentially continuous suite of mixtures of olivine and orthopyroxene. The addition of Ca-rich pyroxene phases (clinopyroxene - cpx) to these assemblages will produce shifts in Band I (and Band II) to

longer wavelengths with an increasing amount of Ca^{2+} (Adams, 1974). This shift displaces the asteroid Band I center above the ol+opx mixing line (Gaffey et al., 1993).

The same 24 objects are plotted in Figure 3b, which illustrates generalized spectral zones for five potential meteorite analogs for S-complex asteroids on a modified version (Burbine et al., 2001; Dunn et al., 2013) of the S-subtype plot. Mineralogic calibrations using stony-meteorite samples have been developed to correlate asteroid spectral band parameters to the following zones: the BA zone using howardite, eucrite, and diogenite (HED) meteorites (Burbine et al., 2009), the S(IV) zone using *H*, *L*, and *LL* ordinary chondrite (hereafter OC) meteorites (Dunn et al., 2010a; Dunn et al., 2010b), and the S(I) zone using mono-mineralic olivine (R-chondrite, brachinite, pallasite) meteorites (Reddy et al., 2011; Sanchez et al., 2014). These mineralogic calibrations have been successful at discriminating mineral chemistry and modal abundance differences within these meteorite groups. Nine Hungaria background asteroids plot within in the S(IV) or “OC boot” zone in Figures 3a and 3b. Two of these asteroids, 1453 Fennia and 4142 Dersu-Uzala, have such similar Band I centers and BARs (see Table 3) that their symbols are superimposed. Additionally, nine other asteroids plot just outside the boundaries of the S(IV) zone: five sub-S(IV) boundary, three near the S(III)/S(IV) boundary, and one supra-S(IV) boundary object. A total of seven asteroids, the five sub-S(IV) asteroids plus two objects that clearly fall within the S(VI) zone of Figure 3a, plot within the acapulcoite-lodranite spectral analog zone (Figure 3b). Two asteroids plot within the S(VII) zone, which is proposed to be analogous with the achondrite mesosiderite group and/or the primitive achondrite lodranite group (Gaffey et al., 1993). It is evident from Figure 3b that two main meteorite groups appear to be represented among the Hungaria background asteroids: unmelted, nebular *L* and/or *LL* OCs and partially-melted primitive achondrites of the acapulcoite-lodranite meteorite clan. The Bus-DeMeo taxonomy, S-subtype, and potential meteorite analog for these 24 S-complex Hungaria background asteroids are provided in Table 5. **None of the S-complex asteroids plot within the S(I) and only two S(VII) asteroids plot within error bars of the BA region (Figure 3a). Therefore, we concentrate on mineralogic interpretations and potential meteorite analogs for the S(IV) OC zone (§ 4.2.1.) and the acapulcoite-lodranite zone (§ 4.2.2.).**

4.2.1. Ordinary Chondrite S(IV) “OC Boot” Mineralogic Interpretations

The S(IV) spectral zone defined by Gaffey et al. (1993) is associated with OC meteorites. The OC meteorite class is divided into three groups *H*, *L*, and *LL* based on the bulk iron contents: *H* chondrites have high total iron contents, *L* chondrites have low total iron contents, and *LL* chondrites have low total iron as well as low metallic iron relative to total iron (Krot et al., 2007). The OCs increase in oxidation state from *H* to *L* to *LL*. Thereby, as their metallic iron content decreases, the FeO contents of their olivines and pyroxenes increase. The *H* chondrites have the lowest fayalite (Fa = mol% iron in olivine) and ferrosilite (Fs = mol% iron in pyroxene) contents and *LL* chondrites have the highest Fa and Fs contents. Dunn et al. (2010a and 2010b) derived calibration equations for determining the olivine and pyroxene **mineralogies** of the *H*, *L*, and *LL* groups of the OC class via spectral and cosmochemical analysis of 48 OC meteorites. Through the use of these calibrations ~80% of asteroids that plot within the S(IV) zone should be correctly classified as potential *H*, *L*, or *LL* parent bodies (Dunn et al., 2010a). The equations relate Band I centers (BIC) to Fa (Eq. 4) and Fs (Eq. 5), and BAR to the olivine/(olivine+pyroxene) ratio [hereafter ol/(ol+px)] (Eq. 6). Mineralogical results for 18 S-complex asteroids [9 S(IV), 3 S(III)/S(IV), and 6 supra- or sub-S(IV)] using these equations are shown in Table 5.

$$Fa = -1284.9 \times (BIC)^2 + 2656.5 \times (BIC) - 1342.3 \quad (4)$$

$$Fs = -879.1 \times (BIC)^2 + 1824.9 \times (BIC) - 921.7 \quad (5)$$

$$ol/(ol+px) = -0.242 \times BAR + 0.728 \quad (6)$$

The spectra of nine Hungaria background asteroids that plot in, or within error bars of, the S(IV) zone are shown in Figure 4. We compare our mineralogic results for these S(IV) asteroids with the Dunn et al. (2010a) equations for Fa content versus ol/(ol+px) that define three boxed regions for the *H*, *L*, and *LL* OC groups (Figure 5). A plot of Fs content versus ol/(ol+px) yield similar OC group meteorite analog results as Figure 5 and is not shown. The uncertainties inherent in the calibration equations (crossbar in Figure 5), ± 1.3 mol% Fa and ± 0.03 ol/(ol+px), are larger than the propagated errors from the band parameter analysis, except for 3873 Roddy, which has an error of ± 0.04 for ol/(ol+px). The mineralogical results given by the calibration

equations narrow down the probable meteorite analog for these nine Hungaria background asteroids (red squares) as *L* and/or *LL* chondrite meteorites (Table 5 and Figure 5). However, it is unclear whether five sub-S(IV) asteroids (blue diamonds), which plot near the bottom border of the S(IV) zone and the top of the acapulcoite-lodranite spectral zone (Figure 3b), are analogous to *H* chondrites or possibly to primitive achondrites of the acapulcoite-lodranite meteorite clan. We explore the possible asteroid-meteorite connection with primitive achondrites for these five asteroids in Section 4.2.2 below. The implications of asteroid-meteorite connections with OCs in regard to possible parent body sources within the Hungaria region are discussed in Section 5.1.1.

4.2.2. Primitive Achondrite Meteorite Spectral Band Parameters

Primitive achondrites of the acapulcoite-lodranite meteorite clan represents rocks that are solid residues remaining from low-degrees (~1-20%) of partial melting of **chondritic material** (McCoy et al., 1996; McCoy et al., 1997b; McCoy et al., 2000). Acapulcoites show very low-degrees of partial melting (~1-5%) and have been heated to ~950-1050°C, warm enough to induce some Fe,Ni-FeS cotectic melting (Mittlefehldt et al., 1996; McCoy et al., 1996; McCoy et al., 1997b). Lodranites show higher-degrees of partial melting than acapulcoites, as they have been heated to ~1050-1200°C, hot enough to produce basaltic partial melts (Mittlefehldt et al., 1996; McCoy et al., 1997a; McCoy et al., 2000). The acapulcoite-lodranite clan is thought to originate from a single, lithologically-diverse, partially-differentiated parent body (Mittlefehldt et al., 1996; McCoy et al., 1997b, McCoy et al., 2000). Acapulcoites and lodranites are uncommon meteorites (Krot et al., 2007) with the type specimen for each group (Acapulco and Lodran, respectively) being the only known recovered falls among the clan⁹. This clan provides evidence that partially-melted material exists among the asteroids. These meteorites therefore provide a basis for spectral comparison with S-complex asteroids in the search for partially-differentiated asteroids.

To examine mineralogic interpretations and potential asteroid-meteorite connections with Hungaria background S-complex asteroids that are not associated with the OC S(IV) spectral zone, we obtained the VIS+NIR spectra of six primitive achondrites (3 acapulcoites, 2 lodranites, and 1 transitional acapulcoite-lodranite) from the RELAB database (Figure 6a). To empirically

⁹ Meteoritical Bulletin Database: <http://www.lpi.usra.edu/meteor/metbull.php>

compare meteorite spectra to asteroid surfaces, which are blanketed in regolith, we selected ground particulate (<125 μm fraction) primitive achondrite spectra from the database. We measured the band parameters of these spectra using the same SARA algorithm (see § 4.1) used for the S-complex asteroids. The results are listed in Table 4. The Band I versus BAR values for the **primitive achondrites** plotted in Figure 6b show that four of the six meteorites plot within the acapulcoite-lodranite spectral zone. **The boundaries of the acapulcoite-lodranite spectral zone shown in Figure 6b are based on the band parameter analysis of a small number of primitive achondrite meteorites (Burbine et al., 2001), and consequently should only be considered generalized boundaries.**

The two recovered falls, Acapulco and Lodran, exhibit minimal terrestrial weathering compared to acapulcoite-lodranite meteorite finds. **These two samples therefore offer suitable representatives** of the generalized acapulcoite-lodranite spectral zone (**Figures 3b and 6b**). Both samples plot within the acapulcoite-lodranite spectral zone near the top boundary, although there is some overlap with the bottom boundary of the OC spectral zone. **Regarding the meteorite finds, one** acapulcoite (ALH 81187) has a much lower BAR than the other meteorite samples and plots outside of any potential meteorite analog spectral zone. This is possibly due to the effects of terrestrial weathering as this sample shows moderate to severe weathering (Antarctic Weathering Category of B/C)¹⁰. **The presence of iron hydroxides due to terrestrial weathering may partially affect spectral band parameter results (Lucas et al., 2016).** Acapulcoite ALH 81261 plots just above the acapulcoite-lodranite spectral zone, in the OC spectral zone. Although both ALH 81187 and ALH 81261 plot outside of the acapulcoite-lodranite analog spectral zone, Band I centers show a narrow range of values between 0.920- and 0.930- μm for all six meteorites. The average Band I center of (0.924 μm ; see blue-dashed line in Figure 6a) for the six primitive achondrites is consistent with the seven Hungaria background S-complex asteroids (Figure 7) that cluster in the acapulcoite-lodranite spectral zone (Figure 3b). **Furthermore, mineralogy derived from the Dunn et al. (2010a) equations [Fa, Fs, and ol/(ol+px)] for five sub-S(IV) asteroids (1750 Eckert, 3225 Hoag, 3635 Kruetz, 5806 Archieroy, and 26471 2000 AS152) are similar (Table 5) and plot just within or below the bottom boundary of the H chondrite spectrally-derived region (Figure 5). None of these five asteroids lie within the H chondrite XRD-derived region obtained from the analysis of OC**

¹⁰ Curation | Antarctic Meteorites: <http://curator.jsc.nasa.gov/antmet/index.cfm>

meteorites. Because these five asteroids plot near a region of the acapulcoite-lodranite spectral zone that overlaps with the OC spectral zone (Figure 3b), their mineralogies warrant further consideration. For asteroids that plot in the immediate vicinity of the OC spectral zone, the Dunn et al. (2010a) equations may offer reasonable estimates of their mineralogies (Dunn et al., 2013). Nonetheless, the mineralogic estimates for sub-S(IV) asteroids (Table 5 and Figure 5) using these equations should be considered with caution. Two S(VI) asteroids (2131 Mayall and 19164 1991 AU1) and two S(VII) asteroids (1019 Strackea and 17408 McAdams), were not analyzed using the Dunn et al. (2010a) equations. Gaffey et al. (1993) suggested possible meteorite analogs of lodranites, winonaites, and IAB irons for the S(VI) subtypes, all of which are partially-melted primitive achondrite meteorites. In agreement with this interpretation, we suggest that primitive achondrites are the most probable meteorite analog for the two S(VI) asteroids and the five sub-S(IV) asteroids mentioned above (Lucas and Emery, 2014). The implications of asteroid-meteorite connections with primitive achondrites in regard to possible parent body sources within the Hungaria region are discussed in Section 5.1.2.

[Table 4 – Band Parameter Analysis for Primitive Achondrite Meteorites]

[Table 5 – Hungaria background S-subtype, mineralogy, and potential meteorite analog]

4.2.3. Hungaria Family Member Asteroid-Meteorite Connections

Spectral homogeneity of the collisional fragments that comprise asteroid families is regularly observed, as family members are typically found to have similar albedos and taxonomies (Cellino et al., 2002). Fittingly, published VIS+NIR spectra of family namesake and largest collisional fragment 434 Hungaria (Gaffey et al., 1992; Kelley and Gaffey, 2002; Clark et al., 2004) and VIS spectra of several Hungaria family members (Fornasier et al., 2008) have shown that they are spectrally consistent with taxonomic E-type asteroids (Tholen taxonomy; Tholen, 1989).

Tholen taxonomic E-types are defined by high albedo (avg. $\rho_v=0.536$, DeMeo and Carry, 2013) and relatively flat spectra, with low to medium reddish slopes. **In the Bus-DeMeo system (DeMeo et al., 2009), albedo is not included in the taxonomic classification scheme.**

This system uses principal component analysis (PCA) to define taxonomic classes, and the majority of the relatively flat spectra of X-complex asteroids (which include E-, M-, and P-types defined in previous taxonomies) are defined by visible-wavelength features. For the Bus-DeMeo Xe-type, these features include slight to moderate slopes ($0.2 < \text{Slope} < 0.38$) and a weak absorption at $\sim 0.49 \mu\text{m}$. Therefore, NIR-only data generate non-unique taxonomic classifications in PCA space (DeMeo et al., 2009). Hence, for our Hungaria family members we report the spectral types of the two lowest residuals (Table 2). In these cases, visual inspection or quantitative comparison of PCA residuals of the asteroid spectrum to the mean spectrum for each class may help determine the most likely spectral type (DeMeo et al., 2009).

Weak absorption features, centered at $\sim 0.9 \mu\text{m}$ due to iron-poor orthopyroxene (Fs_{2-4}) and at $\sim 0.5 \mu\text{m}$ for the sulfide mineral oldhamite (Ca,MgS), are cautiously attributed to these two minerals in some E-type asteroids (Gaffey et al., 1992; Fornasier et al., 2008). Gaffey and Kelley (2004) and Clark et al. (2004) have identified three distinct mineralogies within known E-type asteroids, we use the classification scheme of Clark et al. (2004), who categorized them in reference to three eponymous asteroids: Nysa-like, Angelina-like, and Hungaria-like. Rivkin et al. (1995) found evidence for a $3 \mu\text{m}$ absorption band indicating the presence of hydrated minerals (i.e., mineral containing either OH^- or H_2O) on the surface of 44 Nysa and possibly for 64 Angelina. The presence of hydrated minerals is inconsistent with the igneous nature of **enstatite achondrite meteorites (i.e., aubrites)**, which have experienced temperatures $\geq 1580^\circ\text{C}$ (Keil, 1989), causing further ambiguity regarding the mineralogy of E-type asteroids. Clark et al. (2004) conclude that **aubrites**, which are commonly associated with E-types, are not derived from Nysa-like (0.9- and $1.8\text{-}\mu\text{m}$ absorption bands) and Angelina-like (0.5- and $0.9\text{-}\mu\text{m}$ absorption bands) E-types, but are spectrally consistent with the Hungaria-like E-types ($0.9 \mu\text{m}$ absorption band only). Correspondingly, other workers have proposed that E-types in the Hungaria region are related to the aubrite meteorite group (Gaffey et al., 1992; Kelley and Gaffey, 2002; Čuk et al., 2014).

NIR spectra have been published of only two Hungaria *family* members, 434 Hungaria and 1103 Sequoia (Clark et al., 2004). Figure 8 shows the spectra of four additional Hungaria family members (VIS+NIR - 6447 Terrycocle; NIR - 7087 Lewotsky, 7173 Sepkoski, and 55854 1996 VS1) observed during **this first phase of HARTSS** compared with 1103 Sequoia and with

the largest collisional fragment 434 Hungaria (Clark et al., 2004). Family members 6447 Terrycole, 7087 Lewotsky, and 1103 Sequoia have Xe-type taxonomies, although 1103 Sequoia could also be an Xc-type (Table 2). C-complex asteroids appear to be uncommon among the Hungaria region asteroids with only two objects (~5%) uncovered during HARTSS - family member 55854 1996 VS1 has a taxonomic type of Cgh, and background object 6618 1936 SO is a blue-sloped B-type asteroid (Table 2). Spectra of family members 7087 Lewotsky and 55854 VS1 include **NIR-only data**, and the Bus-DeMeo classification is non-unique. Without VIS spectral data, whether these two asteroids are spectrally and perhaps compositionally similar with 434 Hungaria is inconclusive. Family member 7173 Sepkoski has a Q- or Sq-type taxonomy (Table 2 and Figure 8), and displays significant 1- and 2- μm absorption features, inconsistent with the flat spectra of the other five family members. This result could possibly provide evidence for a heterogeneous Hungaria parent body, or alternatively, 7173 Sepkoski is an interloper and incorrectly included within the membership of the family. We use caution regarding the interpretation of the spectrum of 7173 Sepkoski here, especially considering the NIR data were acquired during poor seeing conditions (see § 2.2) and the spectrum is without VIS data.

5. Discussion

The spectral observations **and analysis** presented herein, reveal significant compositional diversity among Hungaria region asteroids. Among Hungaria background asteroids, our results show evidence for two main potential meteorite analogs: unmelted, nebular *L* chondrites (and possibly *LL* chondrites), and partially-melted primitive achondrites of the acapulcoite-lodranite meteorite clan. **Among the Hungaria collisional family, we find that three of the five smaller Hungaria family members analyzed are spectrally consistent with the largest collisional fragment 434 Hungaria. This asteroid is considered to be related to fully-melted aubrite meteorites (Gaffey et al., 1992; Kelley and Gaffey, 2002; Čuk et al., 2014).** These meteorite groups have experienced a considerable range of peak temperatures, which leads to fundamental petrogenetic differences for their respective parent bodies. *L* chondrites represent nebular materials that have experienced thermal metamorphism, with peak metamorphic temperatures between 700 and 800 °C (Wlotzka, 2005). Acapulcoites have been heated to ~950-1050 °C,

warm enough to produce metal and sulfide partial melts (McCoy et al., 1997b). Lodranites show higher-degrees of partial melting than acapulcoites, with peak temperatures $\sim 1050\text{-}1200\text{ }^{\circ}\text{C}$, hot enough to produce basaltic partial melts (McCoy et al., 1997a; McCoy et al., 2000). Aubrite meteorites may represent pyroxene-rich mantle material from a differentiated asteroid (Gaffey et al., 1992) and have experienced temperatures $\geq 1580\text{ }^{\circ}\text{C}$ (Keil, 1989), high enough to fully melt enstatite. If these asteroid-meteorite connections are truly representative of the material stored in the Hungaria region, then asteroids in the Hungaria region exhibit a full range of petrologic evolution. These results imply that asteroids with very dissimilar petrologic histories coexist in the same region of orbital space.

This compositional diversity is inconsistent with the classic model (**Gradie and Tedesco, 1982**) in which a well-ordered temperature and compositional gradient spanned radially across the **Main Belt** of asteroids. In **that** scenario, asteroid parent bodies that formed in the same region of the PPD should share similar compositional characteristics. However, a more recent paradigm has emerged in which giant planet migration functioned as an efficient mixer, interspersing different asteroid types throughout the **Main Belt** (Tsiganis et al., 2005; Gomes et al., 2005; Walsh et al., 2012), especially asteroids of smaller size (DeMeo and Carry, 2013; DeMeo and Carry, 2014). We then consider a scenario in which the inner portion of the primordial asteroid belt (E-belt) underwent compositional mixing during giant planet migration, which depleted the E-belt between $a \sim 1.7$ **and** ~ 2.0 AU (Bottke et al., 2012), but in the process preserved a fraction of this ancient material in the Hungaria region. This E-belt scenario implies that the present Hungaria asteroids sample material that originated in the inner-most portion of in the primordial asteroid belt closest to the terrestrial planet region. These surviving samples represent only 0.1-0.4% of the initial E-belt population (Bottke et al., 2012) and only $\sim 0.02\%$ of the mass of the current inner belt (DeMeo and Carry, 2013). However sparse this material may be, these samples can reveal much about the composition of the planetesimals in the inner PPD from which the terrestrial planets accreted.

5.1. Meteorite Parent Body Sources Within the Hungaria Region

To further strengthen connections between Hungaria region asteroids and analog meteorites, spectral analysis is coupled with the following lines of evidence to provide a

more coherent picture of source regions and potential parent bodies for specific meteorite groups: 1) the spectral and compositional uniqueness of potential parent bodies, 2) dynamical considerations for the delivery of asteroidal material to Earth via mean-motion and secular resonance “escape hatches”, and 3) clustering of meteorite cosmic-ray exposure (CRE) ages (Cloutis et al., 2014). Taken together, these multiple considerations provide evidence to decipher the origin of the meteoritic material that originates in the Hungaria region and to verify the composition of primordial asteroids stored there. We discuss each of these considerations below for asteroid-meteorite connections uncovered during HARTSS: *H*, *L*, and *LL* OC mineralogies (§ 5.1.1.), primitive achondrites (§ 5.1.2.), and the enstatite achondrites (aubrites) (§ 5.1.3.).

5.1.1. Ordinary Chondrite Parent Body Sources Within the Hungaria Background

Among the nine Hungaria background S-complex objects that plot within the S(IV) zone (Figure 3a; spectra shown in Figure 4), we find that the majority plot within the mineralogic boundaries of the *L* chondrites. Asteroids 2047 Smetana, 3309 Brorfelde, 3873 Roddy, and 5905 Johnson plot within the *L* chondrite spectrally-derived box (Figure 5). A similar inspection of the *LL* chondrite spectrally-derived box shows that 4674 Pauling and 5577 Priestley have *LL* chondrite mineralogies (Figure 5). In addition, four more asteroids that plot near the S(IV) zone [three S(III)/S(IV) and one supra-S(IV); blue diamonds in Figure 5] likely have *L*- or *LL*-mineralogies. 5641 McCleese plots on the *L* chondrite boundary and we include this object as an *L* chondrite object, but 1509 Esclangona lies outside of both of the *L* and *LL* chondrite regions (Figure 5). However, in an independent spectral analysis of 1509 Esclangona (from a separate NIR spectral observation), Lindsay et al. (2015) found this asteroid to be an S(IV) subtype with an *L* chondrite mineralogy. We therefore include 1509 Esclangona in our tally of *L* chondrite objects. 2074 Shoemaker and the supra-S(IV) object 9069 Hovland are clearly within the spectrally-derived box of the *LL* chondrites (Figure 5). Asteroids 1453 Fennia, 4142 Dersu-Uzala, and 7086 Bopp have mineralogies that cannot be distinguished between *L* and *LL* chondrites. All five sub-S(IV) objects lie below the *H* chondrite XRD-measured region (Figure 5), with asteroids 3635 Kruetz and 26471 2000 AS152 **completely** outside of the *H* chondrite spectrally-derived box (Figure 5). Overall, out of 18 Hungaria background S-complex asteroids

with potential OC analogs shown in Figure 5, we find the following abundances: **~17% *H* chondrite mineralogies (including three sub-S(IV) objects at the bottom of the *H* chondrite box)**, ~33% *L* chondrite mineralogies, ~22% *LL* chondrite mineralogies, and ~28% have mineralogies that cannot be distinguished between *H*, *L*, or *LL* chondrites.

Several large NIR spectral datasets of NEAs (Vernazza et al., 2008; de León et al., 2010; Dunn et al., 2013; Thomas et al., 2014) have provided a good portrait of the distribution of OC mineralogies in near-Earth space. Comparing this distribution to potential parent-body source regions is a useful test of the delivery of asteroids to near-Earth space. The OC abundances in the Hungaria region from HARTSS listed above differ from results obtained from these NEA surveys, which have a breakdown of ~15-27% *H* chondrites, ~10% *L* chondrites, and ~42-63% *LL* chondrites (Vernazza et al., 2008; Dunn et al., 2013; Thomas et al., 2014). The surplus of *LL* chondrite mineralogies among NEAs is puzzling as the meteoritic material that arrives to Earth should reflect the population of objects in near-Earth space, but fall percentages for *H*, *L*, and *LL* chondrites are 34.1%, 38.0%, and 7.9% of *total* meteorite falls, respectively (Burbine et al., 2002). These abundances correspond to *H*, *L*, and *LL* chondrites as ~43%, 47%, and 10% of *OC falls*.

The mismatch between the *LL* chondrite abundances within the Hungaria background and the NEA population is not surprising, however, as the major source region for *LL* chondrite NEAs is associated with the Flora asteroid family (Vernazza et al., 2008), with delivery via the ν_6 secular resonance located at the innermost edge of the **Main Belt** (Figure 1). Furthermore, de León et al. (2010) found that only 8% of NEAs are sourced from the Hungaria region. Therefore there is no reason to expect similar abundances among the Hungaria region as found within inner **Main Belt** sources. Although we find different OC abundances from those found in the NEA spectral surveys, it is clear that there is nothing unique about the spectral signatures of OC-like Hungaria background S-complex asteroids obtained during HARTTS. Similar *H*-, *L*-, and *LL*-like spectra and mineralogies are common to the NEA population as discussed above. Similar spectra and mineralogies are common in the **Main Belt** as well, as all three OC groups have proposed parent body source regions located there as discussed below.

We find a prevalence of *L* chondrite mineralogies among OC-like background S-complex objects (~33%) in the Hungaria region. This abundance could be as high as ~50% with the addition of three objects that cannot be distinguished between *L* or *LL* chondrite mineralogies

(Figure 5). Does this abundance reveal the presence of an *L* chondrite parent body among the Hungaria background? We consider dynamical arguments and CRE ages of recent *L* chondrites to explore this question. Nesvorný et al. (2009) argue that both abundant “fossil” shocked *L* chondrites of mid-Ordovician age (467 ± 2 Ma) and recent shocked *L* chondrites are related to the Gefion collisional family of asteroids. The collisional breakup of the Gefion parent body at ~ 470 Ma (^{39}Ar - ^{40}Ar shock age - Korochantseva et al., 2007) quickly delivered an intense bombardment of meteoroids to the Earth via the Jovian 5:2 mean-motion resonance at $a = 2.83$ AU, as evidenced by the mid-Ordovician age of the limestone strata containing the “fossil” *L* chondrites and their extremely short cosmic ray exposure (CRE) ages (0.05-1.5 Myr – Heck et al., 2004). Nesvorný et al. (2009) model a dynamical mechanism that delivers recent shocked *L* chondrites to the Earth through a slower route by drifting inward to the Jovian 3:1 mean-motion resonance at $a = 2.5$ AU. The CRE ages obtained in this model agree with the median CRE age of 20 Myr for recent *L* chondrites (Marti and Graf, 1992; Eugster et al., 2006), which have the longest median CRE age of the OC groups (*H*, *L*, and *LL* median CRE ages of 7 Myr, 20 Myr, and 15 Myr, respectively). In a NIR spectral survey of asteroids located near the Jovian 3:1 mean-motion resonance, Fieber-Beyer and Gaffey (2014; 2015) found three objects just beyond the 3:1 resonance that have *L* chondrite mineralogies and propose a small *L* chondrite genetic family located in the vicinity.

The presence of *L* chondrite mineralogies in our sample of Hungaria background asteroids suggests an independent source region for *L* chondrite material, or alternatively a dynamical mechanism to emplace this material in the Hungaria region from elsewhere. Two secular resonances with Saturn (ν_6 and ν_{16}) and the Jovian 4:1 mean-motion resonance are situated between the Hungaria region and the Jovian 3:1 mean-motion resonance at 2.5 AU (Figure 1). Hungarias are located interior to these strong resonances. Consequently, the delivery route of meteoroids from the Hungaria region to the Earth is different than those with origins in the **Main Belt**. Aubrite meteorites, which are thought to originate from the Hungaria family (Gaffey et al., 1992; Kelley and Gaffey, 2002; Čuk et al., 2014), provide a test of this hypothesis. Aubrites have CRE ages ranging from 13-117 Myr, with a median of 50 Myr (Lorenzetti et al., 2003). These ages are significantly longer than those of other stony meteorites that arrive via **Main Belt** resonances and are therefore consistent with a delivery mechanism distinct from the **Main Belt**. Cuk et al. (2014) modeled the delivery time of meteoroids to Earth by way of

leakage from the inner boundary of the Hungaria region (~ 1.7 AU) and found a good match with the range of CRE ages of aubrite meteorites. The CRE ages of *L* chondrites show peaks at ~ 20 -30 Myr and at ~ 40 Myr (Marti and Graf, 1992), which overlap several aubrites with shorter CRE ages. If Hungaria family fragments can be delivered to Earth in this manner, then fragments of a potential *L* chondrite parent body among the Hungaria background may experience a similar delivery route.

Interestingly, the Hungaria background may harbor a second ancient collisional family comprised of S-types at slightly higher inclinations (Williams, 1992 – Family ID# 191; Milani et al., 2010). However, this putative genetic family is thinly spread out, and therefore has not been confirmed. Perhaps the prevalence of *L* chondrite mineralogies within our sample of Hungaria background S-complex objects reflect surviving collisional fragments of this cryptic family. The acquisition of additional NIR spectra of Hungaria background asteroids may be able to strengthen this possible connection.

We find $\sim 22\%$ *LL* chondrite mineralogies among our OC-like background S-complex objects. This abundance could be as high as $\sim 40\%$ with the addition of three objects that cannot be distinguished between *L* or *LL* chondrite mineralogies (Figure 5). Several studies regarding the source regions of the NEA population (de León et al., 2010; Thomas and Binzel, 2010; Dunn et al., 2013) and a study regarding the mineralogy of multiple asteroid systems (Lindsay et al., 2015) have corroborated the results of Vernazza et al. (2008), who proposed an asteroid-meteorite connection between the Flora collisional family and the *LL* chondrites. The Flora family is located near the v_6 secular resonance with Saturn in the inner **Main Belt** (Figure 1), an efficient escape hatch for leakage of kilometer-size asteroids out of the inner **Main Belt** (Nesvorný et al., 2002). If *LL* chondrite asteroids are firmly linked to the Flora family and delivered to near-Earth space via the v_6 secular resonance, why are *LL* chondrite mineralogies found among our sample of Hungaria background asteroids? Warner et al. (2009) found that the Hungaria region is susceptible to bombardment from Flora asteroids at their perihelia, providing a possible source of *LL* chondrite mineralogies in the Hungaria region. Furthermore, McEachern et al. (2010) proposed a scenario in which some transient Mar-crossing asteroids can be fed into stable orbits in the Hungaria region. They suggest that 5-10% of the Hungaria background population is adopted in this manner with S-complex asteroids being the most likely “adoptees.” Perhaps one or both of these mechanisms has supplied asteroids with *LL* chondrite mineralogies

into the Hungaria region. However, the shorter median CRE age of ~ 15 Myr for *LL* chondrites is consistent with a **Main Belt** source region such as the v_6 secular resonance as opposed to the longer delivery times proposed by Čuk et al. (2014) for the Hungaria region.

We find three questionable *H* chondrite mineralogies out of five sub-S(IV) asteroids (Figure 5). This gives an abundance of potential *H* chondrite mineralogies out of the OC-like background S-complex objects of $\sim 17\%$. Considering our comparison of spectral band parameters between the acapulcoite-lodranite meteorites discussed in § 4.2.2, we suggest that primitive achondrites are the best meteorite analog for these five sub-S(IV) asteroids. If this interpretation is correct, then just as significant as the potential meteorite analogs that are present among our sample of Hungaria background asteroids are the potential meteorite analogs that are absent. An inspection of (Figures 3a and 3b) reveals an obvious gap between asteroids in the upper portion of the OC boot and the five sub-S(IV) asteroids that plot just below it. Similarly, Figure 5 shows a noticeable gap between Hungaria background objects with *L* and *LL* chondrite compositions and the five sub-S(IV) objects that plot just within or outside of the *H* chondrite composition. We interpret this gap in OC-like compositions as an indication that the Hungaria region is not a significant source region for *H* chondrite meteorites. The apparent absence of *H* chondrite material in the Hungaria region is consistent with the probable association of the **Main Belt** asteroid 6 Hebe situated near the Jovian 3:1 mean-motion resonance with *H* chondrite meteorites (Gaffey and Gilbert, 1998). Supporting this association, Thomas and Binzel (2010) found an enhanced preference for a 3:1 mean-motion resonance “express” delivery source for *H* chondrites, consistent with the dynamical model of Bottke et al. (2002b) for the orbital distribution of near-Earth objects and with the relatively short median CRE ages of 7 Myr for *H* chondrites.

5.1.2. Primitive Achondrite Parent Body Sources Within the Hungaria Background

We find that the most probable meteorite analog for two S(VI) asteroids and five sub-S(IV) asteroids (Figure 3a) are primitive achondrites of the acapulcoite-lodranite clan. This yields an abundance of $\sim 20\%$ (7/36) Hungaria background asteroids that may be associated with primitive achondrite meteorites. This abundance is higher than the $\sim 6\%$ (4/72) primitive achondrite like mineralogies found among NEAs by Dunn et al. (2013). There are few studies

regarding the potential source regions for primitive achondrite meteorites. However, using the dynamical model of Bottke et al. (2002b), Dunn et al. (2013) found a probable source region at the Jovian 3:1 mean-motion resonance for one of the primitive achondrite like mineralogies in their sample of NEAs. Eugster and Lorenzetti (2005) found short CRE ages with a narrow range of values ($\sim 4\text{--}7$ Myr) for ten meteorites from the acapulcoite-lodranite clan. These delivery times to Earth are approximately consistent with the short CRE ages found for *H* chondrites (see above) and indicate an “express” delivery source region such as the 3:1 mean-motion resonance similar to *H* chondrites as opposed to the longer delivery times proposed by Čuk et al. (2014) for the Hungaria region.

If the acapulcoite-lodranite clan has such consistently short CRE ages, why are primitive achondrite like mineralogies found among our sample of Hungaria background asteroids? McCoy et al. (1997b) concludes that a partially-differentiated acapulcoite-lodranite parent body would have a heterogeneous surface composition, and therefore the fragments of this parent body could produce all of the subtypes of S-complex asteroids. This argument could provide an explanation for the diversity of Hungaria background S-complex asteroids found during HARTSS. However, the short CRE ages are not consistent with a parent body source for primitive achondrites within the Hungaria region. Although seven asteroids within the Hungaria background have primitive achondrite like spectral features, the probable parent body source region for primitive achondrite meteorites remains inconclusive. The acquisition of additional Hungaria background asteroid spectra in conjunction with the band parameter analysis of a larger suite of primitive achondrite meteorites may provide additional evidence to resolve this issue.

5.1.3. Enstatite Achondrite Parent Body Sources Within the Hungaria Region

The largest member of the Hungaria family, 434 Hungaria, is classified as an E-type in the Tholen taxonomy (albedo ~ 0.47) and a Xe-type in the Bus-DeMeo taxonomy. Clark et al. (2004) note that 434 Hungaria has a strong absorption at $0.9\text{ }\mu\text{m}$, a relatively shallow spectral slope, and a convex spectral shape. They also note that whereas all Tholen E-types (even those outside of the Hungaria region) seem to share these general characteristics, they differ in details, including whether or not a weak $1.8\text{ }\mu\text{m}$ feature is present. Other members of the Bus-DeMeo X-complex, including some other Xe-types, exhibit an even

broader range of spectra. Assuming that the Hungaria family progenitor was compositionally homogeneous, we would expect all of the family members to have spectra that are very similar to 434 Hungaria's spectrum. An inspection of Figure 8 shows that 1103 Sequoia displays a 0.9 μm feature, like 434 Hungaria, but Clark et al. (2004) also note a weak 1.8 μm feature as well, which is not present in their spectrum of 434 Hungaria. Their mixing model results suggest that Sequoia's spectrum is consistent with aubrite meteorites plus olivine and orthopyroxene. Three Hungaria family members observed during HARTSS (6447 Terrycole, 55854 1996 VS1, and 7087 Lewotsky) exhibit no evidence of 0.5-, 0.9-, and 1.8- μm absorption bands found in other E-type asteroids, although the VIS+NIR spectrum of 6447 Terrycole is considerably noisy at these wavelengths and weak absorption features could be obscured. As discussed in § 4.2.3, Q-type 7173 Sepkoski is a possible interloper to the Hungaria family.

Bus-DeMeo X-complex objects are not restricted to the Hungaria collisional family; we found seven additional X-complex asteroids among Hungaria background objects (Table 2 and Figure 2). Four asteroids: 3169 Ostro, 3940 Larion, 4736 Johnwood, and 6249 Jennifer have Xe-type taxonomies (second residual for 3169, 3940, and 6249), whereas 2048 Dwornik, 2449 Kenos, and 9068 1993 OD classify as Xn-type taxonomies. The Xn-type is a class of neutral spectra with a **narrow**, Nysa-like absorption feature at 0.9 μm that has been added to the X-complex in the latest version of the Bus-DeMeo taxonomy¹¹. Whether these background objects are spectrally, and perhaps compositionally, related to the family is uncertain as all seven background X-complex objects have non-unique taxonomic classifications (Table 2). If these X-complex objects truly are related to Xe-types, finding them among the background is not unusual as there is no *a priori* reason to expect that the parent body of the Hungaria collisional family to be the only asteroid with a Xe-type composition located in the Hungaria region.

Additional VIS+NIR spectra are needed to search Hungaria family Xe-types for the diagnostic 0.9 μm absorption feature, and the absence of the 1.8 μm feature, to corroborate that Hungaria family members truly have “Hungaria-like” spectra. Furthermore, additional albedo measurements will help verify the inferred Xe-type taxonomy of Hungaria family members, as Xe-types have the highest albedo among any other asteroid taxonomic type (DeMeo and Carry, 2013). Finally, detection of 3 μm absorptions indicating the presence of hydrated minerals on the

¹¹ http://smass.mit.edu/_documents/v4flowchartmods.pdf

surface of known Hungaria family members would provide evidence counter to the inferred aubrite mineralogy for the Hungaria family members. Until further spectra of Hungaria family members are acquired via HARTSS, no prediction in regard to the spectral and compositional homogeneity of the Hungaria family and their connection to the aubrite meteorite group is ventured.

6. Summary

Previous studies regarding compositional interpretations of Hungaria region asteroids were mostly limited to colorimetric and VIS spectral data. NIR spectral data expands upon mineralogic interpretations and potential asteroid-meteorite connections through the analysis of 1- and 2- μ m absorption bands due to Fe^{2+} electronic transitions in mafic minerals olivine and pyroxene, which are abundant in many types of stony meteorites. Our spectral data set acquired during HARTSS for these “neighbors” to the terrestrial planet region offers a unique view of their surface mineralogy and potential meteorite analogs, which provide constraints on the composition of the asteroidal material from which the terrestrial planets accreted. Based on our comparison of HARTSS Phase I spectral data to laboratory based meteorite calibrations for OCs and spectral data of primitive achondrite meteorites, we arrive at several conclusions, which are summarized below.

The taxonomic distribution within the Hungaria region indicates that stony S-complex asteroids are prevalent among Hungaria background asteroids (29 of 36 objects; ~80%). These background S-complex objects exhibit considerable spectral diversity as spectral band parameter measurements reveal that several different S-subtypes are represented therein, which translates to a variety of surface compositions. The taxonomic distribution among Hungaria family members shows that three of five smaller fragments observed during HARTSS are consistent with the Xe-type taxonomy of the largest collisional fragment 434 Hungaria. C-complex asteroids are uncommon (2 of 42 objects; ~5%) within the Hungaria region.

We find two main asteroid-meteorite connections among the Hungaria background asteroids, unmelted, nebular *L* ordinary chondrites (and possibly *LL* chondrites), and partially-melted primitive achondrites of the acapulcoite-lodranite meteorite clan. **Laboratory spectra of six primitive achondrite meteorites are spectrally consistent with seven Hungaria**

background asteroids (1750, 2131, 3225, 3635, 5806, 19164, and 26471). We suggest that primitive achondrites are the most probable meteorite analog for these objects. Four fragments of the Hungaria family are spectrally consistent with the largest collisional fragment 434 Hungaria, except 7173 Sepkoski, which has a Q-type spectrum. This result could possibly provide evidence for a heterogeneous Hungaria parent body, or alternatively, 7173 Sepkoski is an interloper and incorrectly included within the membership of the family.

We suggest a source region for *L* chondrite like material from within the Hungaria region with delivery to Earth via leakage from the inner boundary of the Hungaria region. *H* chondrite like mineralogies appear to be absent from the Hungaria background asteroids. We conclude that the Hungaria region is not a source region for *H* chondrite meteorites. Although seven asteroids within the Hungaria background have spectral band parameters consistent with partially-melted primitive achondrites, the probable source region for the acapulcoite-lodranite parent body remains inconclusive. If the proposed connection with the Hungaria family to the aubrite meteorite group is accurate, then asteroids in the Hungaria region exhibit a full range of petrologic evolution: from nebular, unmelted ordinary chondrites, through partially-melted primitive achondrites, to fully-melted igneous aubrite meteorites.

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Appendix

A.1 *NIR Spectral Plots*

This Appendix contains plots of the final reduced VIS+NIR spectra of 42 Hungaria asteroids presented in this paper (Figure A1). The NIR spectral data are supplemented with VIS spectra for 21 asteroids from the following sources: the 24-Color Asteroid Survey (Chapman et al., 1993) for **asteroids** 1019 and 1727; the Small Main-Belt Asteroid Spectroscopic Survey (SMASS) database (Xu et al., 1995) for **asteroid** 2074; the SMASS Phase II database (Bus and Binzel, 2002) for **asteroids** 434, 1103, 2131, 3169, 3635, 3873, 4142, 5641, and 6249; the Small Solar System Objects Spectroscopic Survey (S³OS²) dataset (Lazzaro et al., 2004) for **asteroids** 1509, 1750, 3225, 3940, 6310, and 6447. Visible spectra (0.45-0.85 μm) for **asteroids** 2577, 3309, and 4674 were acquired with the Southern Astrophysical Research (SOAR) telescope using the Goodman High Throughput Spectrometer (Clemens et al., 2004) and were provided by Lindsay et al. (2015). All spectra have been normalized to unity at the isophotal wavelength of *J*-band at 1.25 μm (MKO-NIR filter system; Tokunaga and Vacca, 2007). The gray bars on each plot denote wavelengths of strong absorption by water vapor in Earth’s atmosphere. These absorptions can be difficult to correct for spectra obtained during nights of poor or variable weather, and residual bands can be noticed in several of the spectra.

Figure A1. (continued)

Figure A1. (continued)

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Table 1. Observing circumstances for NIR spectroscopy.

Object	Date (UT)	Time ^e (UT)	Airmass	Mag. (V)	r^e (AU)	g^e ($^{\circ}$)	t_{int} (min)	Solar analog
434 Hungaria ^c	2001	-	-	13.4	-	-	-	Landolt
1019 Strackea	2012 Aug 29	11:16	1.327	14.4	1.869	9.9	24	SAO 191948
1103 Sequoia ^c	2003 Aug 16	-	-	14.1	1.757	19.5	-	L112-1333
1453 Fennia	2012 Sep 18	11:35	1.018	15.2	1.916	18.1	16	SAO 92718
1509 Esclangona	2009 Sep 28	09:19	1.173	15.3	1.927	22.4	24	SAO 36472
1727 Mette	2013 Jan 22	10:25	1.052	13.8	1.686	10.9	16	SAO 115174
1750 Eckert	2013 Jan 22	10:59	1.081	15.3	1.953	10.7	16	SAO 135872
2047 Smetana	2012 Nov 09	09:35	1.002	15.4	1.869	5.6	20	SAO 75191
2048 Dwornik ^c	2003 Aug 16	-	-	15.6	1.896	15.4	-	L112-1333
2074 Shoemaker ^a	2003 Sep 30	10:51	1.008	15.1	1.680	15.5	44	16 CygB
2131 Mayall	2013 Jan 22	11:35	1.186	15.7	2.084	18.2	16	SAO 155741
2449 Kenos ^a	2010 Sep 07	05:28	1.033	16.5	1.627	33.9	24	L110-361
2577 Litva ^b	2012 Apr 10	11:40	1.06	15.8	1.97	18.8	64	HD 165479
3169 Ostro	2013 Oct 31	03:29	1.223	15.7	1.818	30.3	21	L115-271
3225 Hoag	2013 Oct 02	06:27	1.386	14.4	1.798	7.5	16	SAO 128385
3309 Brorfelde ^b	2010 Nov 13	11:45	1.11	15.4	1.91	8.1	32	HD 247554
3635 Kruetz ^a	2005 Nov 12	12:59	1.042	16.0	1.717	14.0	48	Hyades 64
3873 Roddy ^a	2004 Oct 16	06:40	1.403	17.1	2.132	27.8	30	16 CygB
3940 Larion	2013 Oct 02	05:06	1.175	15.8	2.089	20.4	24	SAO 126740
4142 Dersu-Uzala ^d	2002 Apr 15	09:57	1.030	15.2	1.810	22.1	57	Hyades 64
4674 Pauling ^b	2010 Sep 13	09:20	1.02	16.0	1.92	17.3	32	HD 215274
4736 Johnwood	2013 Jan 22	09:51	1.050	15.1	1.781	12.3	16	SAO 59815
5175 Ables	2013 Oct 31	01:43	1.049	15.8	2.020	14.2	24	L98-978
5577 Priestley ^a	2011 Aug 22	12:47	1.955	16.4	1.766	24.8	32	L110-361
5641 McCleese ^a	2005 Apr 11	14:27	1.028	15.8	1.591	31.1	40	L105-56
5806 Archieroy	2012 Sep 18	10:59	1.077	15.6	1.903	19.3	16	SAO 73226
5905 Johnson ^b	2011 Jul 06	12:50	1.43	17.1	1.78	33.4	64	HD 224908
6249 Jennifer ^a	2010 Sep 06	05:37	1.027	16.4	1.801	33.9	32	L110-361
6310 Jankonke	2012 Nov 09	12:58	1.176	15.4	1.874	13.7	16	SAO 131080
6447 Terrycole	2012 Nov 09	12:14	1.034	15.1	1.801	8.9	16	HD 285295
6618 (1936 SO)	2013 Oct 02	05:59	1.294	15.3	1.855	14.5	16	SAO 90982
7086 Bopp	2012 Sep 18	10:26	1.100	15.2	1.762	18.7	16	SAO 90243
7087 Lewotsky	2013 Oct 31	00:59	1.033	15.9	1.936	5.6	24	L115-271
7173 Sepkoski	2013 Oct 31	05:23	1.368	16.0	1.945	12.0	24	L98-978
7187 Isobe	2012 Aug 29	08:34	1.083	15.0	1.858	8.9	32	SAO 127201
9068 (1993 OD)	2013 Nov 24	13:35	1.413	14.9	1.563	26.4	16	SAO 13707
9069 Hovland	2012 Nov 09	11:33	1.088	15.4	1.690	9.4	16	SAO 75787
9873 (1992 GH)	2013 Oct 31	00:31	1.130	15.4	1.734	19.7	12	L98-978
17408 McAdams	2013 Nov 24	14:15	1.309	15.9	1.682	22.3	12	SAO 132749
19164 (1991 AU1)	2012 Aug 29	09:59	1.152	14.9	1.929	1.4	32	SAO 165008
26471(2000 AS152)	2012 Nov 09	13:39	1.093	15.4	1.905	18.9	16	SAO 58093
55854 (1996 VS1)	2012 Nov 09	10:20	1.035	15.6	1.833	5.7	32	SAO 110550

^a Data from MIT-UH-IRTF Joint Campaign for NEO Reconnaissance^b Data from Lindsay et al., 2015^c Data from Clark et al., 2004. **Observing circumstances from Table 2 of Clark et al., 2004.**^d Data from Binzel et al., 2004b^e Time, r , and g given for beginning of observation

Table 2. Hungaria asteroid orbital and physical properties and Bus-DeMeo (BDM) taxonomy.

Object	a (AU)	i (°)	H	p_v^a	Population	BDM Taxonomy ^b
434 Hungaria	1.944	22.510	11.2	0.428	family	Xe, K
1019 Strackea	1.912	26.981	12.6	0.224	background	Sw
1103 Sequoia	1.934	17.900	12.2	0.480	family	Xc, Xe
1453 Fennia	1.897	23.674	12.5	0.249	background	Q, Sq
1509 Esclangona	1.866	22.323	12.6	0.233	background	Sw ^c
1727 Mette	1.854	22.897	12.5	0.258	background	Sw
1750 Eckert	1.926	19.087	13.2	0.258	background	Srw ^c
2047 Smetana	1.872	25.278	13.9	0.258	background	Q, Sq
2048 Dwornik	1.953	23.754	13.5	0.536	background	Xn, L
2074 Shoemaker	1.800	30.075	13.8	0.258	background	Sw
2131 Mayall	1.887	33.995	12.7	0.239	background	Sw
2449 Kenos	1.909	24.985	14.3	0.460	background	Xn, L
2577 Litva	1.904	22.909	13.2	0.258	background	Sw
3169 Ostro	1.892	24.904	12.7	0.183	background	L, Xe ^d
3225 Hoag	1.880	25.062	13.2	0.258	background	S ^c
3309 Brorfelde	1.818	21.134	13.6	0.258	background	Sw
3635 Kruetz	1.794	19.222	14.6	0.258	background	Srw
3873 Roddy	1.892	23.353	12.8	0.258	background	S
3940 Larion	1.988	22.838	12.7	0.183	background	L, Xe ^c
4142 Dersu-Uzala	1.912	26.493	13.0	0.258	background	Srw
4674 Pauling	1.859	19.439	13.8	0.258	background	Sw
4736 Johnwood	1.958	21.966	13.4	0.536	background	Xe, Xc
5175 Ables	1.967	16.844	13.3	0.258	background	Q, Sq ^d
5577 Priestley	1.844	22.271	14.2	0.258	background	Q, Sq
5641 McCleese	1.820	22.203	14.0	0.455	background	Sw
5806 Archieroy	1.963	20.819	12.9	0.258	background	Sq, Q
5905 Johnson	1.910	27.524	14.0	0.258	background	Q, Sq
6249 Jennifer	1.914	28.106	13.0	0.536	background	Xc, Xe
6310 Jankonke	1.913	23.593	14.0	0.258	background	Sw ^c
6447 Terrycole	1.952	19.770	14.5	0.536	family	Xe, Xc ^c
6618 (1936 SO)	1.875	23.831	13.3	0.071	background	B, L
7086 Bopp	1.909	25.616	13.8	0.258	background	Q, Sq
7087 Lewotsky	1.956	19.542	14.1	0.536	family	Xe, Xc ^d
7173 Sepkoski	1.956	19.582	13.9	0.258	family	Q, Sq ^d
7187 Isobe	1.938	21.789	13.9	0.258	background	Sq, K
9068 (1993 OD)	1.820	20.297	13.6	0.536	background	Xn, L
9069 Hovland	1.913	19.571	14.2	0.258	background	Q, Sq
9873 (1992 GH)	1.862	19.232	13.6	0.258	background	Sq, S ^d
17408 McAdams	1.883	25.685	14.2	0.258	background	Sr, S
19164 (1991 AU1)	1.856	22.321	14.0	0.258	background	S, Sq
26471(2000 AS152)	1.918	19.693	13.2	0.258	background	Sq, S
55854 (1996 VS1)	1.930	23.293	14.2	0.083	family	Cgh, Ch

Orbital elements (a, i) at epoch 2457200.5 (2015-Jun-27.0) TDB, reference JPL (heliocentric ecliptic J2000), from <http://ssd.jpl.nasa.gov/sbdb.cgi>, referenced October 26th, 2015

^a Visible geometric albedos from IRAS where available. Values in *italics* are average albedos for taxonomic types taken from DeMeo and Carry, 2013.

^b For asteroids with non-unique Bus-DeMeo taxonomic classifications, the two lowest average residual solutions are listed

^c reflectance values extrapolated from 0.49 μm to 0.45 μm to derive Bus-DeMeo taxonomic classification

^d reflectance values extrapolated from 2.40 μm to 2.45 μm to derive Bus-DeMeo taxonomic classification

Table 3. Band parameter analysis for 24 S-type Hungaria asteroids.

Object	Temp. (K)	BIC	BIC error	BI area ($\times 10^{-2}$)	BI area error ($\times 10^{-2}$)	BIIC	BIIC _{icorr}	BIIC error	BII area ($\times 10^{-2}$)	BII area error ($\times 10^{-2}$)	BAR	BAR _{icorr}	BAR error
1019 Strackea	204	0.920	0.005	2.22	0.13	1.906	1.925	0.062	4.11	0.36	1.86	1.78	0.20
1453 Fennia	201	0.969	0.001	3.91	0.02	1.921	1.941	0.005	1.97	0.04	0.50	0.43	0.01
1509 Esclangona	201	0.961	0.004	3.91	0.07	2.027	2.047	0.114	1.49	0.24	0.38	0.30	0.06
1727 Mette	214	1.024	0.002	5.79	0.04	2.082	2.099	0.022	1.00	0.05	0.17	0.10	0.01
1750 Eckert	199	0.924	0.003	3.50	0.06	1.898	1.918	0.008	4.10	0.12	1.17	1.09	0.04
2047 Smetana	204	0.952	0.004	3.52	0.03	1.932	1.951	0.010	2.44	0.07	0.69	0.61	0.02
2074 Shoemaker	215	0.970	0.001	7.91	0.10	1.930	1.947	0.004	3.10	0.05	0.39	0.32	0.01
2131 Mayall	193	0.917	0.002	1.65	0.03	1.916	1.937	0.015	2.14	0.10	1.29	1.21	0.07
2577 Litva	198	1.044	0.001	6.56	0.03	2.043	2.063	0.005	3.97	0.05	0.60	0.52	0.01
3225 Hoag	208	0.922	0.003	2.01	0.03	2.006	2.024	0.039	2.23	0.13	1.11	1.04	0.07
3309 Brorfelde	202	0.955	0.003	3.99	0.04	1.890	1.910	0.005	3.75	0.09	0.94	0.86	0.03
3635 Kruetz	212	0.920	0.002	5.39	0.05	1.928	1.946	0.008	4.53	0.10	0.84	0.77	0.02
3873 Roddy	191	0.958	0.010	5.31	0.43	1.988	2.010	0.143	4.97	0.74	0.94	0.85	0.16
4142 Dersu-Uzala	207	0.968	0.004	8.60	0.10	1.931	1.949	0.006	4.30	0.10	0.50	0.42	0.01
4674 Pauling	201	1.007	0.003	3.41	0.03	1.922	1.942	0.015	1.47	0.07	0.43	0.35	0.02
5577 Priestley	209	0.988	0.010	3.07	0.16	1.898	1.917	0.033	1.49	0.27	0.49	0.41	0.09
5641 McCleese	216	0.953	0.002	7.25	0.11	1.922	1.938	0.003	3.13	0.04	0.43	0.36	0.01
5806 Archieroy	202	0.925	0.001	3.24	0.03	1.926	1.945	0.007	3.05	0.07	0.94	0.86	0.02
5905 Johnson	208	0.964	0.005	4.02	0.06	1.926	1.944	0.006	2.73	0.10	0.68	0.61	0.03
7086 Bopp	210	0.981	0.002	5.88	0.03	1.942	1.960	0.011	2.79	0.09	0.47	0.40	0.02
9069 Hovland	214	1.017	0.002	7.10	0.03	2.066	2.083	0.017	2.83	0.08	0.40	0.33	0.01
17408 McAdams	215	0.917	0.005	1.79	0.04	1.879	1.896	0.011	3.64	0.20	2.04	1.97	0.12
19164 1991 AU1	200	0.917	0.003	2.23	0.08	1.916	1.936	0.070	3.13	0.21	1.40	1.32	0.11
26471 2000 AS152	202	0.917	0.002	2.61	0.04	1.898	1.917	0.006	2.95	0.09	1.13	1.05	0.04

BIC = Band I center; BIIC = Band II center; BAR = Band Area Ratio; *icorr* = temperature corrected value**Table 4.** Band parameter analysis for primitive achondrite meteorite samples (ground particulate <125 μm fraction).

Meteorite	Group	RELAB ID	BIC	BIC error	BI area ($\times 10^{-2}$)	BI area error ($\times 10^{-2}$)	BIIC	BIIC error	BII area ($\times 10^{-2}$)	BII area error ($\times 10^{-2}$)	BAR	BAR error
ALH 81261	Acapulcoite	TB-TJM-039	0.930	0.002	13.38	0.04	1.870	0.002	8.66	0.03	0.647	0.003
ALH 81187	Acapulcoite	TB-TJM-040	0.930	0.004	5.32	0.05	1.833	0.008	0.97	0.07	0.182	0.013
Lodran	Lodranite	TB-TJM-041	0.920	0.002	13.95	0.05	1.880	0.001	12.10	0.03	0.868	0.004
EET 84302	Acap/Lod	TB-TJM-042	0.920	0.001	10.80	0.06	1.850	0.004	11.44	0.07	1.06	0.009
Acapulco	Acapulcoite	TB-TJM-043	0.923	0.002	13.25	0.04	1.863	0.002	11.32	0.05	0.854	0.005
GRA 95209	Lodranite	TB-TJM-044	0.920	0.002	10.09	0.04	1.857	0.001	7.77	0.03	0.770	0.005

BIC = Band I center; BIIC = Band II center; BAR = Band Area Ratio

Table 5. Hungaria background asteroid S-subtype, mineralogy, and potential meteorite analog.

Object	BDM	S-sub	Fa (mol%)	Fs (mol%)	ol/(ol+px)	Meteorite analog
1019 Strackea	Sw	S(VII)	-	-	-	mesosiderite?/lodranite? ^a
1453 Fennia	Q, Sq	S(IV)	25.3	21.1	0.62	<i>L</i> or <i>LL</i> chondrite
1509 Esclangona	Sw	S(III)/S(IV)	24.0	20.2	0.66	ureilite?/ <i>L-LL</i> chondrite?
1727 Mette	Sw	-	-	-	-	olivine-rich?
1750 Eckert	Srw	sub-S(IV)	15.4	14.0	0.47	<i>H</i> chondrite?/acap-lod?
2047 Smetana	Q, Sq	S(IV)	22.1	18.8	0.58	<i>L</i> chondrite
2074 Shoemaker	Sw	S(III)/S(IV)	25.6	21.3	0.65	ureilite?/ <i>LL</i> chondrite?
2131 Mayall	Sw	S(VI)	-	-	-	acap-lod?/winonaite? ^a
2577 Litva	Sw	S(II)	-	-	-	cpx-rich ureilite?/brachinite? ^a
3225 Hoag	S	sub-S(IV)	14.6	13.5	0.48	<i>H</i> chondrite?/acap-lod?
3309 Brorfelde	Sw	S(IV)	22.8	19.3	0.52	<i>L</i> chondrite
3635 Kruetz	Srw	sub-S(IV)	14.1	13.1	0.54	<i>H</i> chondrite?/acap-lod?
3873 Roddy	S	S(IV)	23.5	19.8	0.52	<i>L</i> chondrite
4142 Dersu-Uzala	Srw	S(IV)	25.3	21.1	0.63	<i>L</i> or <i>LL</i> chondrite
4674 Pauling	Sw	S(IV)	29.8	24.5	0.65	<i>LL</i> chondrite
5577 Priestley	Q, Sq	S(IV)	28.1	23.2	0.63	<i>L</i> or <i>LL</i> chondrite
5641 McCleese	Sw	S(III)/S(IV)	22.5	19.1	0.64	ureilite?/ <i>L</i> chondrite?
5806 Archieroy	Sq, Q	sub-S(IV)	15.6	14.1	0.52	<i>H</i> chondrite?/acap-lod?
5905 Johnson	Q, Sq	S(IV)	24.5	20.6	0.58	<i>L</i> chondrite
7086 Bopp	Q, Sq	S(IV)	27.2	22.5	0.63	<i>L</i> or <i>LL</i> chondrite
9069 Hovland	Q, Sq	supra-S(IV)	30.4	25.0	0.65	<i>LL</i> chondrite
17408 McAdams	Sr, S	S(VII)	-	-	-	mesosiderite?/lodranite? ^a
19164 1991 AU1	S, Sq	S(VI)	-	-	-	acap-lod?/winonaite? ^a
26471 2000 AS152	Sq, S	sub-S(IV)	13.3	12.5	0.47	acapulcoite-lodranite?

^a possible meteorite analog for S-subtypes from Table VI of Gaffey et al. (1993)

Figure 1. The inner portion of the Main Belt of asteroids shown in osculating i versus a space indicating the location of the Hungaria dynamical region. Major perihelion secular resonances with Saturn are indicated by blue dotted lines. The Jupiter 4:1 mean-motion resonance is indicated by the brown thick-dashed line. The red thin-dashed line indicates the exterior Mars 2:3 mean-motion resonance, which appears to bound the outer edge of the Hungaria region. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article).

Figure 2. Numbered Hungaria region asteroids (~ 6100) with absolute magnitude (H_v) ≤ 18.0 in H_v versus a space. Largest collisional fragment and family namesake 434 Hungaria (green triangle) and family members (small gray diamonds) are thought to be spectrally homogeneous. **Hungaria family Yarkovsky curves (gray-dashed curved lines) are delineated as in Warner et al. (2009).** Hungaria background asteroids (i.e., non-family) are indicated by small black circles. Family members plotted with proper a , background asteroids plotted with osculating a . Large symbols show the taxonomic classification of our sample of 42 Hungaria asteroids. **Large symbols with asteroid numbers indicate the six Hungaria family members from our sample.** S-complex (red squares) asteroids are prevalent ($\sim 80\%$) among the Hungaria background population. X-complex (large green diamonds) asteroids are spectrally consistent with 434 Hungaria and its collisional fragments represented by family members. C-complex (large blue circles) asteroids are uncommon among our sample ($\sim 5\%$). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article).

Figure 3. Band I center versus BAR for 24 Hungaria background S-complex asteroids (solid squares). **(a)** Band I center versus BAR shown relative to the S(I)-S(VII) and basaltic achondrite (BA) zones of Gaffey et al. (1993), the thick black curve indicates the location of the olivine-orthopyroxene mixing line (Cloutis et al., 1986). **(b)** Band I center versus BAR shown relative to spectral zones analogous to potential meteorite groups. The olivine, ordinary chondrite, and basaltic achondrite zones are from Gaffey et al. (1993); the primitive achondrite zone is from Burbine et al. (2001), the ureilite zone is from Cloutis et al. (2010). For both (a) and (b) the symbols for two objects (1453 Fennia and 4142 Dersu-Uzala) plot on top of each other in the ordinary chondrite zone at Band I center ~ 0.97 and BAR ~ 0.43 . For both (a) and (b) the 1σ errors for Band I center and BAR from Table 3 are plotted for each object (for some objects the error is smaller than the symbol size).

Figure 4. Spectra of nine Hungaria background asteroids that plot within the Gaffey S(IV) subtype region zone of Figure 3a, VIS+NIR spectra for the lower four asteroids, NIR-only data for the upper five asteroids. All spectra are normalized to unity at 1.20 μm and are offset for clarity. Most spectra show noise at $\sim 1.4 \mu\text{m}$ and $1.9 \mu\text{m}$ (gray regions) due to incompletely corrected telluric bands. Note the shallow $2 \mu\text{m}$ feature for all spectra.

Figure 5. The mol% Fa in olivine versus ol/(ol+px) ratio for 18 Hungaria background S-complex asteroids. The S(IV) subtypes are indicated by red squares, the S(III)/S(IV), and supra- and sub-S(IV) subtypes that plot near the boundary but not within the S(IV) “OC boot” (see Figures 3a and 3b) are indicated by blue diamonds. The dashed boxes show the ranges of ol/(ol+px) measured via X-ray diffraction by Dunn et al. (2010b) and the range of Fa contents in *H*, *L*, and *LL* ordinary chondrites (Brearley and Jones, 1998). The solid boxes are larger and include the errors in the calibration equations for the spectrally derived values (± 0.03 for ol/(ol+px) and 1.3 mol% for Fa; represented by the crossbar). Error for ol/(ol+px) for 3873 Roddy is ± 0.04 . (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article).

Figure 6. Primitive achondrite meteorite spectra obtained from the RELAB database. **(a)** VIS+NIR spectra of six primitive achondrite meteorites, Acapulco, ALH 81187, and ALH 81261 are acapulcoites, EET 84302 is a transitional acapulcoite-lodranite, and Lodran and GRA 95209 are lodranites. Blue-dashed line indicates the average Band I center of $0.924 \mu\text{m}$ for these six meteorites. Spectra are normalized to unity at $1.20 \mu\text{m}$ and are offset for clarity. See Table 4 for band parameter values. **(b)** Band I center versus BAR for the six primitive achondrites (open triangles) from (a). Spectral zones that are analogous to potential meteorite groups are the same as Figure 3b. The 1σ errors for Band I center and BAR from Table 3 are on the order of the symbol size.

Figure 7. Spectra of seven Hungaria background asteroids that plot in the Gaffey S(VI) or below the S(IV) subtype region [sub-S(IV) in Table 5] of Figure 3a, and in the spectral zone analogous to acapulcoites-lodranites from Figure 3b, VIS+NIR spectra for the lower four asteroids, NIR-only data for the upper three asteroids. All spectra are normalized to unity at 1.20 μm and are offset for clarity. Blue-dashed line indicates the average Band I center of 0.924 μm for the six primitive achondrite meteorites from Figure 6a. Most spectra show noise at $\sim 1.4 \mu\text{m}$ and $1.9 \mu\text{m}$ (gray regions) due to incompletely corrected telluric bands.

Figure 8. Spectra for six Hungaria family member asteroids, VIS+NIR spectra for the lower three asteroids, NIR-only data for the upper three asteroids. All spectra are normalized to unity at 1.20 μm and are offset for clarity. Most spectra show noise at $\sim 1.4 \mu\text{m}$ and $1.9 \mu\text{m}$ (gray regions) due to incompletely corrected telluric bands. Reflectance data between ~ 1.75 - $1.95 \mu\text{m}$ for 7087 Lewotsky and 7173 Sepkoski are not shown for clarity.