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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). 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

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region for *L* chondrite like material from within the Hungarias, 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 conclude that the Hungaria region is not a source 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) (Fig. 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), 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 ∼14,000 known, small (D< 11 km) asteroids (JPL Horizons[1]) 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 (PDS[2] 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 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 > ∼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-µm 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- µm 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

[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.