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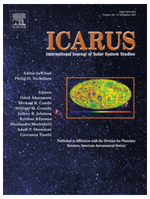

Portrait of the Polana–Eulalia family complex: Surface homogeneity revealed from near-infrared spectroscopy

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ABSTRACT

The inner asteroid belt is an important source of near-Earth asteroids (NEAs). Dynamical studies of the inner asteroid belt have identified several families overlapping in proper orbital elements, including the Polana and Eulalia families that contain a large fraction of the low-albedo asteroids in this region.

We present results from two coordinated observational campaigns to characterize this region through near-infrared (NIR) spectroscopy. These campaigns ran from August 2012 to May 2014 and used the NASA Infrared Telescope Facility and the Telescopio Nazionale Galileo. The observations focused on objects within these families or in the background, with low albedo ($p_v \leq 0.1$) and low inclination ($i_P \leq 7°$). We observed 63 asteroids (57 never before observed in the NIR): 61 *low-albedo* objects and two interlopers, both compatible with S- or E- taxonomical types.

We found our sample to be spectrally homogeneous in the NIR. The sample shows a continuum of neutral to moderately-red concave-up spectra, very similar within the uncertainties. Only one object in the sample, *asteroid (3429) Chuvaev*, has a blue spectrum, with a slope ($S' = -1.33\pm\ 0.21\%/1000$ Å) significantly different from the average spectrum ($S' = 0.68\pm\ 0.68\%/1000$ Å). This spectral homogeneity is independent of membership in families or the background population. Furthermore, we show that the Eulalia and Polana families cannot be distinguished using NIR data. We also searched for rotational variability on the surface of (495) Eulalia which we do not detect. (495) Eulalia shows a red concave-up spectrum with an average slope $S' = 0.91\pm\ 0.60\%/1000$ Å, very similar to the average slope of our sample.

The spectra of two targets of sample-return missions, (101955) Bennu, target of NASA's OSIRIS-Rex and (162173) 1999 JU$_3$ target of the Japanese Space Agency's Hayabusa-2, are very similar to our average spectrum, which would be compatible with an origin in this region of the inner belt.

1. Introduction

The inner asteroid belt (henceforth inner belt) is an important source of near-Earth asteroids (NEAs) with a complex dynamical history (e.g., Dykhuis and Greenberg, 2015). The two current targets of sample-return missions are believed to originate in the inner belt, either in the families of primitive asteroids or in the background population (e.g., Campins et al., 2010; 2013; Bottke et al., 2015). These are asteroids (101955) Bennu, target of NASA's OSIRIS-Rex (Lauretta et al., 2010) and (162173) 1999 JU$_3$, target of the Japanese Space Agency's Hayabusa-2 (Tsuda et al., 2013).

Asteroid families (sometimes also called collisional families) are produced by the collisional breakup or cratering of a parent body

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(Nesvorny et al., 2015). Families can be identified dynamically because they appear as a group in the proper element space even giga-years after the original collision. Although the orbital elements of the fragments in an asteroid family remain linked, they spread over time, primarily in semimajor axis, due to the thermal forces of the Yarkovsky/YORP effect (see Bottke et al., 2002, 2006, 2015; Nesvorny et al., 2015; Vokrouhlický et al., 2015). The YORP effect can modify the rotation rates and obliquities of small bodies, and the Yarkovsky effect can produce significant secular changes in semimajor axis over timescales that vary from millions to billions of years. The rate of change of the semimajor axis due to the Yarkovsky effect is $\sim 10^{-4}$ AU/My and scales proportional to the asteroid's obliquity and inversely proportional to the diameter of the object. Its effect is negligible for bodies with $D \gtrsim 40$ km (Bottke et al., 2002). Because many asteroid families are hundreds of millions of years to billions of years old, these drifts are large enough to explain the observed dispersions of many asteroid families. Depending on the location and age of a family some of its members will drift into the several mean motion and secular resonances that cross the Main asteroid belt, which can produce rapid and dramatic orbital changes. This can result in several outcomes that include evolution to a near-Earth orbit, impacting the Sun, and ejection from the Solar System (Morbidelli et al., 2002, and references therein). There are also numerous diffusive resonances crossing the Main belt of asteroids that have been shown to be an important source of near earth asteroids (NEAs, Morbidelli and Vokrouhlický, 2003).

The Polana and Eulalia families are the low-albedo component of the Nysa–Polana complex[1] (Walsh et al., 2013, Nesvorny, 2012, 2015). This complex is located in the inner belt, between the ν_6 secular resonance, near 2.05 AU and the 3:1 mean motion resonance with Jupiter at 2.5 AU. Moreover, these families coexist in the space of proper orbital elements with a background of low-albedo asteroids that is also a possible source of some low-albedo NEAs (Campins et al., 2013, 2010; Delbo and Michel, 2011).

The origin and evolution of inner belt families is rather interesting (e.g., see Dykhuis and Greenberg, 2015, and references therein). As of 2013, four distinct low-albedo asteroid families were typically identified in the low inclination region of the inner belt: Clarissa, Erigone, Sulamitis and Polana. In 2013 Walsh et al. (2013) identified two families of primitive asteroids with low inclinations in the region previously associated with the Polana family. They named these two families the "new Polana" (with 142 Polana as the parent body) and the "Eulalia" (with 495 Eulalia as the parent body). They did not find compositional variety based on colors from the Sloan Digital Sky Survey (SDSS). However, according to previous spectroscopic observations (Fieber-Beyer et al., 2008, de León et al., 2012, and the MIT-UH-IRTF Joint Campaign for NEO Reconnaissance) Walsh et al. (2013) proposed that NIR spectroscopy could help distinguishing both families. According, Walsh et al. (2013) suggested that objects in the Polana family would have a neutral to red spectrum[2] in the NIR while on the contrary, objects in the Eulalia family would have a blue spectrum[3] in the NIR.

Independently, Dykhuis and Greenberg (2015) described a complex picture with many overlapping inner belt families. In the population of dark asteroids within the Nysa–Polana region they identified three different dynamical families, one related to (142) Polana and two related to (495) Eulalia. The results indicated that they all have similar colors within the given Sloan Digital Sky Survey (SDSS) wavelength range.

Recently, Vokrouhlický et al. (2016) showed how the orbit of (495) Eulalia, known to be long-term dynamically unstable, is also affected by the Yarkovsky effect that pushes the asteroid to longer semi-major axis. The authors estimate that this evolution could result in (495) Eulalia falling into the 3:1 resonance with Jupiter in $\sim$ 0.2–1 Gyr. At that moment, the Eulalia family will become "orphan", with no parent asteroid.

Catalogs of asteroid families evolve due to changing detection techniques and dynamical criteria; physical data, such as albedo, size distribution function, colors and spectra complement the dynamical information of families. In 2012, our group started a spectroscopic study of what was then known as the Polana family, which Nesvorny et al. (2015) now calls the Polana–Eulalia families. The aim of our study was to characterize the primitive asteroid population in this region of the inner belt and better constrain the origin of asteroids (101955) Bennu and 1999 JU_3. We performed two NIR spectroscopic campaigns using two different telescopes: the 3.6 m Telescopio Nazionale Galileo (TNG) and the 3.0 m NASA's Infrared Telescope Facility (IRTF).

In this work, we present the results from these two NIR spectroscopic campaigns. Our observations include three new spectra of (495) Eulalia at different rotational phases covering a whole rotation. Most of our targets in the Polana–Eulalia family complex (including objects that have not been identified as members of either family) have very similar spectra. In other words, the spectroscopic evidence suggests that the complex dynamical history did not result in compositional diversity in this region. Visible spectra of objects in these two families are reported in a companion article by de León et al. (2016) and there is also no evidence of spectrally distinct primitive populations at the shorter wavelengths (in agreement with the results of Dykhuis and Greenberg, 2015; Walsh et al., 2013).

2. Target selection

An important aspect of this work is target selection. The data presented here was obtained in two separate, but coordinated observational campaigns. Both of the campaigns (described in detail below) targeted low-albedo ($p_v \leq 0.1$) and low-inclination ($i_P \leq 7^o$) asteroids located between the ν_6 and 3:1 resonances, which correspond to proper semi-major axes (for this inclination) of $\sim$ 2.05 and 2.5 AU, respectively.

Family membership is based on values of the proper semimajor axis (a), proper eccentricity (e), proper inclination (i) and on the absolute magnitudes (H) as a function of proper semimajor axis (a). To determine this membership we extended Walsh et al. (2013) modeling of the region by incorporating albedo data from the post-cryogenic NASA Wide-field Infrared Survey Explorer (WISE) mission (Masiero et al., 2012). The proper orbital elements of the Polana–Eulalia family members (see Walsh et al., 2013 for a description of family determination and membership) are similar in semimajor axis, with the Polana family being older and more extended in both eccentricity and inclination than the Eulalia family (see Fig. 1).

The two families also have considerable overlap in *Hvsa* space (see Fig. 2). In this space each family is bounded by the "Yarkovsky curves", which are essentially a size-dependent envelope around the center of the family (generally assumed to be the proper semimajor axis of the largest remnant of the family), indicating the furthest that a family member could drift, due to Yarkovsky effect, as a function of its size (Vokrouhlický et al., 2006). For the case of the Polana–Eulalia family complex, we can define three regions. As shown in Fig. 2 the first region is labeled *P* and includes asteroids within the Polana family, but outside the Eulalia family (i.e., region

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[1] To connect our work with future efforts, we identify the Nysa–Polana complex with the Family Identification Number (FIN) of 405, assigned to the region by Nesvorny et al. (2015).

[2] A red spectrum presents a positive spectral slope in the wavelength range from 0.8 to 2.2 μm, i.e., increasing reflectance with increasing wavelength.

[3] A blue spectrum presents a negative spectral slope in the wavelength range from 0.8 to 2.2 μm, i.e., decreasing reflectance with increasing wavelength.