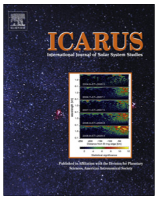
Icarus 225 (2013) 283–297

Contents lists available at SciVerse ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus



Introducing the Eulalia and new Polana asteroid families: Re-assessing primitive asteroid families in the inner Main Belt

Kevin J. Walsh [a,*], Marco Delbó [b], William F. Bottke [a], David Vokrouhlický [c], Dante S. Lauretta [d]

[a] Southwest Research Institute, 1050 Walnut St., Suite 400, Boulder, CO 80302, USA
[b] UNS-CNRS-Observatoire de la Côte d'Azur, BP 4229, 06304 Nice cedex 04, France
[c] Institute of Astronomy, Charles University, V Holešovičkách 2, 18000 Prague 8, Czech Republic
[d] Lunar & Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA

ARTICLE INFO

Article history:
Received 13 December 2012
Revised 19 February 2013
Accepted 2 March 2013
Available online 2 April 2013

Keywords:
Asteroids
Near-Earth objects
Planetary dynamics

ABSTRACT

The so-called Nysa–Polana complex of asteroids is a diverse and widespread group studied by Cellino et al. (Cellino, A., Zappalà, V., Doressoundiram, A., di Martino, M., Bendjoya, P., Dotto, E., Migliorini, F., 2001. Icarus 152, 225–237) as a dynamically linked asteroid family. It carries the name of two asteroids because it appears to be two overlapping families of different asteroid taxonomies: (44) Nysa is an E-type asteroid with the lowest number in the midst of a predominantly S-type cluster and (142) Polana is a B-type asteroid near the low-albedo B-and C-type cluster. The latter has been shown to be a very important source of primitive near Earth asteroids.

Using the data from the Wide-field Infrared Survey Explorer (WISE) mission we have re-analyzed the region around the Nysa–Polana complex in the inner Main Belt, focusing on the low-albedo population. (142) Polana does not appear to be a member of the family of low-albedo asteroids in the Nysa–Polana complex. Rather, the largest is Asteroid (495) Eulalia. This asteroid has never before been linked to this complex for an important dynamical reason: it currently has a proper eccentricity slightly below the range of most of the family members. However, its orbit is very close to the 3:1 mean motion resonance with Jupiter and is in a weak secular resonance. We show that its osculating eccentricity varies widely ($e = 0.06$–0.19) on short timescales ($\sim$1 Myr) and the averaged value diffuses (between $e = 0.11$–0.15) over long timescales ($\sim$100 Myr). The diffusive orbit, low-albedo, taxonomic similarity and semimajor axis strongly suggests that despite its current proper eccentricity, (495) Eulalia could have recently been at an orbit very central to the family. Hierarchical Clustering Method tests confirm that at an eccentricity of $e = 0.15$, (495) Eulalia could be the parent of the family. The "Eulalia family" was formed between 900 and 1500 Myr ago, and likely resulted from the breakup of a 100 to 160 km parent body.

There is also compelling evidence for an older and more widespread primitive family in the same region of the asteroid belt parented by Asteroid (142) Polana. This family, the "new Polana family", is more extended in orbital elements, and is older than 2000 Myr.

1. Introduction

1.1. NEO origins

Near-Earth objects (NEOs) are temporary visitors in the region around the terrestrial planets, and significant work has gone into understanding their dynamical behavior and lifetimes. Gladman et al. (2000) and others found that NEOs have short lifetimes, only about 10 Myr on average. Gravitational perturbations from planets, collisions with the terrestrial planets, or loss into the Sun or ejection out of the Solar System limit their average lifetimes. Contrasted with the age of the Solar System, the much shorter NEO lifetimes suggest that today's NEOs are simply the current incarnation of a constantly re-filled steady-state population. Cratering records (Grieve and Shoemaker, 1994; Stöffler and Ryder, 2001) find that the impact flux on the terrestrial planets and the Moon has been relatively constant on Gyr timescales, supporting the idea of a steady-state population.

The problem of how to refill NEO space from the seemingly static Main Asteroid belt was answered with the discovery that asteroids are quite mobile (Bottke et al., 2000, 2006). Thermal forces work via the Yarkovsky-effect to change asteroid's semimajor axes over time (Farinella and Vokrouhlický, 1999; Bottke et al., 2000,

---

* Corresponding author.
E-mail address: kwalsh@boulder.swri.edu (K.J. Walsh).

0019-1035/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.icarus.2013.03.005

2001; see also a review by Bottke et al. (2006)). This discovery provided the key piece of physics needed to understand how Main Belt asteroids become NEOs. It had been known that some of the more powerful resonances located near, or in, the Main Asteroid belt could rapidly excite asteroid's eccentricities, sending them onto planet-crossing orbits leading to their delivery to NEO orbits. The Yarkovsky effect showed how to efficiently get asteroids into these resonances.

The two most important resonances for this delivery process are readily visible in a plot of the asteroid belt. First, the 3:1 mean motion resonance (MMR) with Jupiter is located at heliocentric distance ~2.5 AU, and is responsible for the large gap in the asteroid distribution at this semi-major axis. The other is the ν_6 secular resonance, which occurs when the precession frequency of an asteroid's longitude of perihelion is equal to the mean precession frequency of Saturn. This resonance is inclination dependent, and is very efficient at delivering low-inclination bodies to NEO orbits. It is the effective inner edge of the asteroid belt at ~2.15 AU, and estimated to deliver ~37% of all NEOs with $H < 18$ (Bottke et al., 2002).

The inner Main Belt (IMB; $2.15 < a < 2.5$ AU)—bound by these two resonances—is a predominant source of NEOs. Dynamical models predict that ~61% of the $H < 18$ NEO population comes from there. The majority of the detected IMB asteroids, ~4/5 those with $H < 15.5$, are on low-inclination orbits ($i < 8°$). Although a compositional gradient is known to exist in the Main Belt, with low-albedo, primitive asteroids being predominant in the central (2.5 AU < a < 2.8 AU) and the outer asteroid belt ($a > 2.8$ AU) (Gradie and Tedesco (1982); Mothé-Diniz et al., 2003; Masiero et al., 2011), the IMB contains numerous primitive asteroids (Campins et al., 2010; Gayon-Markt et al., 2012; Masiero et al., 2011). For instance, in a sample of WISE-studied asteroids limited to absolute magnitude $H < 15$, about 1/6 of these bodies in the IMB with measured albedos and sizes have geometric visible albedos $p_V < 0.1$, where we use $p_V < 0.1$ as a simple way to separate low-albedo primitive bodies from more processed or igneous bodies typically with higher albedos.

Recent studies devoted to finding the origin of the primitive NEOs 1999 RQ_{36}, 1999 JU_3, and 1996 FG_3 (baseline targets of the sample return space missions, OSIRIS-REx, Hayabusa-II, and Marco Polo-R) have found that each of these three bodies are almost certainly (>90%) delivered from the IMB following the well-studied dynamical pathway from the Main Belt to NEO-orbits (Campins et al., 2010, 2012,, 2000, 2002). Moreover, the current low inclination ($i < 8°$) orbits of these bodies is indicative of origins on similarly low inclination orbits in the Main Belt. Furthermore, Jenniskens et al. (2010), and Gayon-Markt et al. (2012) have identified the IMB at low inclination ($i < 8°$) as the likely source (>90%) of the NEO 2008 TC_3, the asteroid whose impact produced the Almahata Sitta meteorites.

The work presented here develops the fundamental hypotheses to be tested by planned asteroid sample return missions. Dynamical evolution studies are critical to obtaining the maximum scientific benefit from these missions. Such studies support primary mission objectives to characterize the geologic and dynamic history of the target asteroids and provide critical context for their returned samples. In addition, cosmochemical analyses of e.g., cosmogenic isotope ratios, radionuclide abundances, and nuclear track densities will, in return, provide important constraints on the dynamical evolution of the parent asteroid. This synergy will result in improved understanding of the dynamical pathways that transform IMB objects into NEOs. Furthermore, the OSIRIS-REx mission specifically will provide the first ground-truth assessment of the Yarkovsky effect as it relates to the chemical nature and dynamical state of an individual asteroid. These studies will provide important input to models of the evolution of asteroid families by Yarkovsky drift and delivery to orbital resonances in the IMB.

1.2. Asteroid families and the Nysa–Polana complex

The landscape of the inner Main Belt is dominated by a handful of asteroid families and a diffuse population of "background" objects (see Fig. 1). Among primitive, low-albedo, bodies the largest known family is the low-albedo component of the Nysa–Polana complex, followed by the Erigone family and the Sulamitis family (Nesvorný 2010; Nesvorný, 2010; Gayon-Markt et al., 2012; Campins et al., 2012). Following an asteroid break-up event, fragments are launched onto orbits that are distinct from, but similar to, the parent body. Specifically, their "proper orbital elements", roughly the long-term average of their osculating orbital elements, remain linked over time (Zappalá et al., 1990, 1994; Knežević and Milani, 2003). Smaller fragments are typically launched with higher velocity, creating a size-dependent spread in orbital elements. Over time the thermal Yarkovsky effect induces a size-dependent drift in semi-major axis, such that smaller bodies drift faster, and thus further, over time than the larger bodies. Therefore families of asteroids are identifiable in two ways: clustering in proper orbital element space, and correlated shapes in size vs. semimajor axis due to size-dependent Yarkovsky drift (see Vokrouhlický et al., 2006a; Bottke et al., 2006).

In the context of NEO-delivery, the size, age and location of an asteroid family are important properties. First, the larger the family, the more potential asteroids that can be delivered. Second, the age of a family determines how far it has spread by the Yarkovsky-effect, where older families can spread further. Finally, the location of the family determines how far its fragments must drift via the Yarkovsky effect to reach a resonance. As we find with the Nysa–Polana complex, a location very near a resonance makes locating

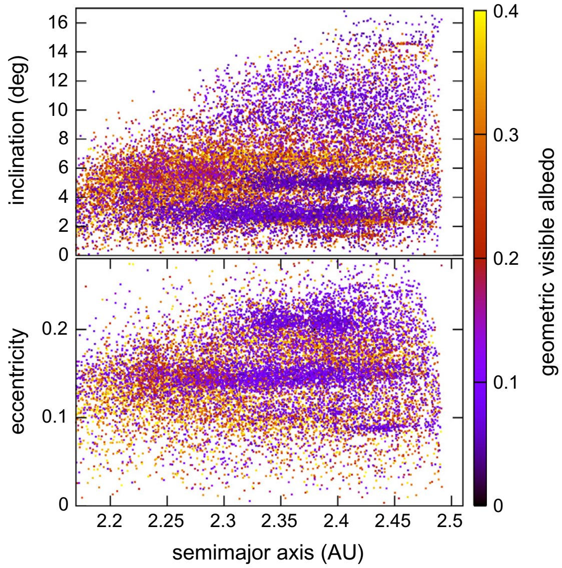


Fig. 1. The entire inner Main Belt, including all asteroids that were observed by WISE and whose D and p_V were published in the Preliminary release of Albedos and Diameters (Masiero et al., 2011) plotted using computed synthetic proper elements (Knežević and Milani, 2003). The plots show the orbital inclination and the eccentricity as a function of their semimajor axis (AU). The color of each point represents their WISE-determined albedo with values shown in the colorbar on the right (Masiero et al., 2011). The low-albedo component of the Nysa–Polana complex is visible as the large low-albedo complex at $e \sim 0.15$ and $i \sim 3°$ extending across almost the entire IMB. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)