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On the V-type asteroids outside the Vesta family

II. Is (21238) 1995 WV7 a fragment of the long-lost basaltic crust of (15) Eunomia?

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ABSTRACT

Context. The V-type asteroids are associated with basaltic composition. Apart from (1459) Magnya, an asteroid that is clearly dynamically and mineralogically unconnected to the Vesta family, all currently known V-type asteroids are either members of the Vesta family, or are hypothesized to be former members of the dynamical family that migrated to their current orbital positions. The recent identification of (21238) 1995 WV7 as a V-type asteroid introduces the possibility that a second basaltic asteroid not connected with the Vesta family exists. This asteroid is on the opposite side of the 3:1 mean motion resonance with respect to Vesta, and it would be very unlikely that a member of the Vesta family of its size ($D > 5$ km) migrating via either the Yarkovsky effect or repeated close encounters with Vesta survived the passage through such a resonance.

Aims. In this work we investigate the possibility that (21238) 1995 WV7 originated as a fragment of the parent body of the Eunomia family and then migrated via the interplay of the Yarkovsky effect and some powerful nonlinear secular resonances, such as the $(s - s_6) - (g_5 - g_6)$. If (15) Eunomia is, as claimed, a differentiated object whose originally pyroxene-enriched crust layer was lost in a collision that either created the Eunomia family or preceded its formation, can (21238) be a fragment of its long-lost basaltic crust that migrated to the current position?

Methods. We mapped the phase space around (21238) and determined which of the nonlinear secular resonances that we identified are stronger and more capable of having caused the current difference in proper i between (21238) and members of the Eunomia family. We simulated the Yarkovsky effect by using the SWIFT-RMVSY integrator.

Results. Our results suggest that it is possible to migrate from the Eunomia dynamical family to the current orbital location of (21238) via the interplay of the Yarkovsky effect and the $(s - s_6) - (g_5 - g_6)$ nonlinear secular resonance, on time-scales of at least 2.6 Gyr.

Conclusions. (15) Eunomia might be the third currently known parent body for V-type asteroids.

Key words. minor planets, asteroids – celestial mechanics

1. Introduction

The V-type asteroids, which are characterized by 1 and 2 μm absorption bands in the infrared spectrum, are associated with basaltic composition. Apart from (1459) Magnya, an asteroid that is clearly dynamically and mineralogically unconnected to the Vesta family (Lazzaro et al. 2000; Michtchenko et al. 2002), all known V-type asteroids are either members of the Vesta family or are hypothesized to be former members of the dynamical family that migrated due to i) the interplay of the Yarkovsky effect with mean-motion and secular resonances (Carruba et al. 2005); or ii) repeated close encounters with (4) Vesta (Carruba et al. 2007). The recent identification of (21238) 1995 WV7 as a V-type asteroid (Binzel et al. 2006; Hammergren et al. 2007) introduces the possibility that it exists a second basaltic asteroid that is not connected with the Vesta family. This asteroid is on the other side of the 3:1 mean motion resonance with respect to Vesta, and it would be unlikely that a member of the Vesta family of the size of (21238) migrating via either the Yarkovsky effect or repeated close encounters with Vesta survived the passage of such a powerful resonance: assuming a diameter between 5 and 9 km, a spin obliquity of 60°, and typical Yarkovsky parameters for basaltic objects (see Sect. 4), the maximum drift-rate for a regolith-covered body is $\simeq 1{-}2 \times 10^{-5}$ AU/Myr. Assuming a uniform drift rate (i.e., no re-orientations), it would take more than a billion years for (21238) to cross the 3:1 resonance. This time is more than two orders of magnitude greater than the dynamical lifetime of objects within the 3:1 resonance (Gladman et al. 1997).

The question that naturally arises about (21238) 1995 WV7 is about its origin. If not in the Vesta family, then where was it born? The Eunomia family is one of the largest families present in the the middle belt, the region where (21238) resides (see Fig. 1). (15) Eunomia, an asteroid with a diameter of about 255.3 km, has long been known as the remnant of a differentiated, or partially differentiated, body, whose originally

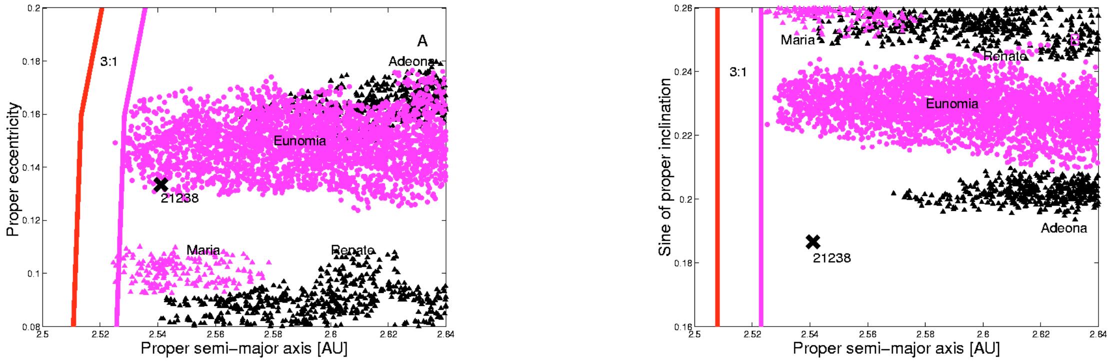

Fig. 1. Proper $a - e$ **a)** and $a - i$ **b)** projections of the region of (21238) 1995 WV7. Magenta dots show the members of the Eunomia dynamical family, black triangles members of the Adeona and Renate families, magenta triangles members of the Maria family, all computed with the HCM method and a cutoff of 55 m/s (Zappalá et al. 1990, 1995, see Sect. 2 for a more detailed discussion of the choice of the cutoff). (21238) is identified by the black ×, and the vertical lines show i) ($a \simeq 2.508$ AU) the limits of the 3:1 mean-motion resonance and ii) ($a \simeq 2.523$ AU) of the chaotic region near the 3:1 resonance, as in Morbidelli & Vokrouhlický (2003). Note how the main difference between (21238) and the members of the Eunomia family is the smaller proper inclination of (21238), while the value of proper e and a are compatible with family membership.

pyroxene-enriched crust layer was lost in the major collision that created the Eunomia family (Reed et al. 1997; Nathues et al. 2005). Lazzaro et al. (1999) indirectly confirmed this picture by observing 44 Eunomia members and showing that the spectra of 41 of them, while consistent with a common origin, show a spread of surface compositions that indicates that the Eunomia family was formed from the fragmentation of a differentiated or partially differentiated S-type parent body (see also Sect. 2.2). Can (21238) 1995 WV7 be a surviving fragment of the long-lost basaltic crust of the parent body of the Eunomia family?

In this work we explore this possibility and verify all possible migration paths that link the Eunomia family to the current orbital location of (21238). We show that at least three important nonlinear secular resonances (for a definition of linear and nonlinear secular resonances see Sect. 3 and Appendix 1 of Carruba et al. 2007) cross the Eunomia family and may have acted as causeways for migration, in a mechanism similar to the one already studied in Carruba et al. (2005) for (809) Lundia and (956) Elisa, and on timescales comparable with the Eunomia family age ((2.5 ± 1.0) Gyr, Nesvorný et al. 2004).

Our simulations suggest that one of these resonances, the $s - s_6 - g_5 + g_6$ resonance, may have caused the observed change in the proper inclination of (21238), while essentially preserving the initial value of proper eccentricity. We also studied the origin of two other asteroids in the region, (40521) 1999 RL95 and (66905) 1999 VC160, identified by Roig & Gil-Hutton (2006) as having albedos obtained by the Sloan Digital Sky Survey Moving Object Catalog (see Sect. 2.3) compatible with a V-type classification. We confirm that their origin can also be explained as being former Eunomia family members. The current ejection velocities of (21238), (40521), and (66905) with respect to (15) Eunomia are 1.0, 1.7, and 0.4 km s^{-1}, respectively. To compute the ejection velocities, we used Eqs. (4)–(6) in Morbidelli et al. (1995) with $f = 80°$ and $\omega = 90°$, where f and ω are the true anomaly and argument of perihelion of the parent body at the moment of impact, respectively.

This work is organized as follows: In the second section we discuss some basic facts about (21238) and the Eunomia family. In the third section we study the dynamics in the region of (21238) and identify all nonlinear secular resonances up to order six, and in the fourth section we study how migration via the Yarkovsky effect is possible and on what timescales. In the fifth section we discuss the possible origin of the two V-type candidates of Roig & Gil-Hutton (2006) as former members of the Eunomia family. Finally, we present our conclusions in the sixth section.

2. Some basic facts about (21238) and the Eunomia family

2.1. The dynamical families in the region

If we want to demonstrate that (21238) is a fragment of the Eunomia parent body, we first need to define the dynamical limits of this family. Asteroid dynamical families are clusters in the space of proper $a - e - i$[1]. The most common way to define a dynamical family is via the hierarchical clustering method of Zappalá (1990, 1995). In this method, a metric in the space of proper elements is defined so as to convert distances in the proper $a, e, \sin(i)$ space into distances in velocity space[2]. Given an asteroid's proper element (we use the proper elements furnished in the asteroid proper elements database of Milani & Knežević 1993)[3], the velocity distance between that asteroid and all the others in the main belt is computed. If the distance is less than a critical value, the velocity cutoff, the asteroid is associated

[1] We must make a distinction between the original family and the nominal family determined with the classical HCM and others methods described in this article. When the asteroid family was formed, their members were thrown in a space already populated by other objects, sometimes having different superficial compositions. Also, the orbits of some of the family members evolved due to the several gravitational and non-gravitational effects described in the article. Therefore, when applying methods such as the HCM, we find clusters of objects in the current proper element or frequency space (Carruba & Mitchtchenko 2007) that may or not have the same origin. Also, these methods may miss some of the asteroids that evolved farther away from the family core. When using the word "family" we usually refer to the agglomeration of objects found with the methods described in this article, keeping in mind that the relationship of these clusters with the original agglomeration of objects created in the collisional event is generally a very complicated one.

[2] The most commonly used metric is

$$v = n \cdot a \cdot \sqrt{1.25 \cdot \left(\frac{\Delta a}{a}\right)^2 + 2 \cdot (\Delta e)^2 + 2 \cdot (\Delta \sin(i))^2}, \quad (1)$$

where n is the proper mean-motion and v, the velocity distance between asteroids is measured in m/s.

[3] http://hamilton.dm.unipi.it/cgi-bin/astdys/astibo

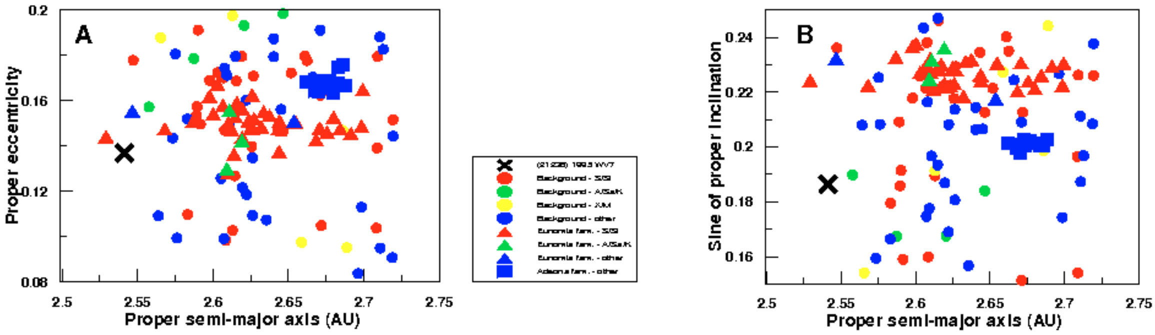

Fig. 2. Taxonomic distribution of asteroids in the region: (*left panel*) semi-major axis versus eccentricity and (*right panel*) semi-major axis versus sine of inclination. Asteroid (21238) 1995 VW7, the unique V-type in the region, is indicated by the black cross.

to the original asteroid family. This process is repeated until no new asteroids are found.

The main problem with this procedure is the determination of the velocity cutoff. There is no a priori value that can be set, and the velocity cutoff is usually a function of the number of asteroids present in the local background, which also depends on the number of asteroids present in the asteroid proper elements' database. The typical procedure is to find the family for several values of the velocity cutoff, until the family coalesces with the local background, enclosing members of other known asteroid families, and then use a value that is ≃10% lower than this critical value, so as not to include too many asteroids not necessarily linked with the family. We applied this method to the Eunomia and other families in the region and found that $v_{\rm cutoff}$ = 55 m/s is a reasonable choice for their velocity cutoff.

In order to understand to what extent the members of the Eunomia dynamical family are connected to the parent body also in terms of composition, we turn our attention to the spectroscopic classification of asteroids in the Eunomia region.

2.2. Compositional analysis

Although the following dynamical studies may indicate that asteroid (21238) 1995 WV7 might be a fragment of (15) Eunomia, we need to analyze whether this possibility agrees with the known compositional/spectroscopic studies. According to Reed et al. (1997), the surface composition of asteroid (15) Eunomia varies from stony-iron to basaltic. Its elongated shape with a different composition at each end tends to indicate that the asteroid is a cross section through a completely or partially differentiated parent body. This result has been confirmed by Nathues et al. (2005) who also finds that a major fraction of Eunomia's surface is enriched in olivine, indicating that a large fraction of the original pyroxene-enriched crust has possibly been lost during the collision giving rise to the Eunomia's large dynamical family, or in previous ones. Among the possible fragments of the long-lost Eunomia crust, the first detected object seems to be (21238) 1995 WV7, although others must exist in the region, if our hypothesis is true. On the other hand, the spectroscopic analysis of 44 members of the Eunomia family (Lazzaro et al. 1999) indicated an overall S-type characterization, but with a quite significant spread of the surface composition. These results agrees with the hypothesis of a differentiated body. Although no significant concentration of metals on the surface of (15) Eunomia have been found anymore than any M-type asteroid in the region, these facts do not exclude the possibility that the parent body of the Eunomia family was a completely differentiated asteroid, since the core could still be embedded under the current surface of (15) Eunomia (as in the case of (4) Vesta).

To gain further insight into the possible genetic origin of asteroid (21238) 1995 WV7, we analyzed the compositional distribution in its neighborhood. The region studied was delimited by the semi-major axis a, eccentricity e, and inclination i, as follows: $2.52 \leq a \leq 2.72$ AU, $0.08 \leq e \leq 0.2$, $0.15 \leq \sin i \leq 0.25$. In this region about 10 000 numbered asteroids exist, including the Eunomia dynamical family and part of the Adeona family. The taxonomic distribution was then obtained by searching for those objects having a classification in the three major photometric/spectroscopic surveys: ECAS (Zellner et al. 1985; Tholen 1989), SMASS (Xu et al. 1995; Bus & Binzel 2002b), and S3OS2 (Lazzaro et al. 2004). According to these surveys, only 131 asteroids have an assigned taxonomic classification, representing about 1% of the objects present in the region.

The classified objects can be roughly separated into "featured" and "featureless" groups, the spectra of the former containing an absorption band around 1 μm, while the latter is roughly linear. It is important to note that the fragmentation of a partially differentiated body would lead to a swarm of objects predominantly of the first group, i.e., of the S-A-V-type, according to the most classical taxonomy (Tholen 1988). On the other hand, the catastrophic disruption of a completely differentiated body would also produce fragments with a "featureless" spectra, of the X- or M-type, coming from the metallic nucleus. In the region, about 60% of the asteroids present "featured" spectra and 40% "featureless" one. Note, however, that among the 40% the large majority of objects are of the C- and D-types, which are incompatible with a differentiated mineralogy. This somehow confirms the trend already, found in the Eunomia family studies, of a lack of metal-rich asteroids in the region.

The complete taxonomic distribution in the defined region is given in Fig. 2, where the unique V-type asteroid in the region, (21238) 1995 WV7, is represented by the black cross. In the figure the triangles and squares represent asteroids members of the Eunomia and Adeona family, respectively, while the dots represent background asteroids. The S- and Sl-type asteroids are indicated by red. The green symbols represent objects with an A, Sa or K classification. The yellow symbols represent objects of the X-type having either a moderate albedo (M-type according to the Tholen taxonomy) or no known albedo. Finally, all other classes are indicated by blue symbols. If asteroid (21238) 1995 WV7 is a segment from the crust of the Eunomia's family parent body, then we would expect to identify several olivine-rich (mainly A-type) objects in the vicinity of (21238) 1995 WV7, but this is not observed. Although a few A-type asteroids are present among the Eunomia family and in its surroundings, none is

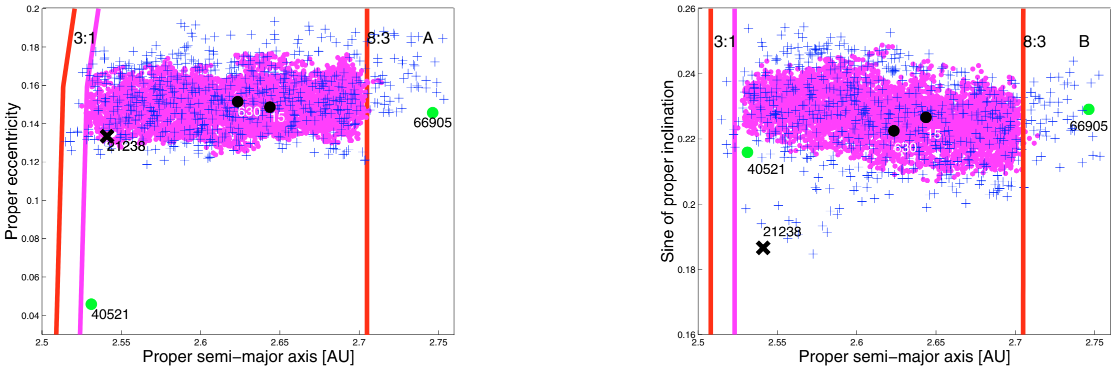

Fig. 3. The $a - e$ and $a - i$ projection of (21238) (black ×), of the other two V-type candidates identified by Roig & Gil-Hutton (2006), (40521) and (66905), green dots, of (630) and (15) (black dots), of members of the Eunomia dynamical family computed with a cutoff of 55 m/s (magenta dots), and of members of the Eunomia family in the extended space of proper elements and colors, with a cutoff of 205 m/s (blue pluses). The vertical red lines at $a = 2.704$ AU show the location of the 8:3 mean-motion resonance. The other lines have the same meaning as in Fig. 1.

really near the V-type object. It is important to note, however, that this might be just a question of the small number of asteroids with known taxonomy, in particular, the smaller ones. More observations are needed to understand the compositional picture of the Eunomia region. To further explore the subject of the composition of the Eunomia's members, we tried to see what information can be found using the photometric data of the SLOAN survey.

2.3. The Eunomia family: the SLOAN data

The Sloan Digital Sky Survey Moving Object Catalog, hereafter SDSS MOC3, lists astrometric and photometric data for asteroids observed by the 2.5-m Sloan telescope located at Apache Point Observatory in Sunspot, New Mexico. To date (3rd release), the survey has determined positions, brightnesses, and five-color CCD photometry of 204 305 moving objects (Ivezić et al. 2001). The 67 636 unique moving objects detected by the survey (i.e., about 28% of the total) have been matched (Jurić et al. 2002) to known asteroids listed in the ASTORB file (Bowell et al. 1994). The flux reflected by the detected objects was measured almost simultaneously in five bands (measurements in two successive bands were separated in time by 72 s) with effective wavelengths 3557 angstrom (u band), 4825 angstrom (g band), 6261 angstrom (r band), 7672 angstrom (i band), and 9097 angstrom (z band), and with 0.1−0.3-μm band widths (Fukugita et al. 1996).

We used this data to find members of the Eunomia family in the extended space of colors and proper elements (Bus & Binzel 2002a; Nesvorný et al. 2004). Using the Roig & Gil-Hutton (2006) approach, we computed the first two principal components PC_1 and PC_2. We then determine the Eunomia family in the extended space of proper elements and colors. Bus & Binzel (2002a) introduced an extended metric in such a space:

$$d_2 = \sqrt{v^2 + C_{PC}[(\delta PC_1)^2 + (\delta PC_2)^2]}, \qquad (2)$$

where v is given by Eq. (1), $\delta PC_i = |PC_i(1) - PC_i(2)|$ with $i = 1, 2$, and C_{PC} is a numerical factor, usually set equal to 10^6, if v is measured in m/s (values in a range between 10^4 and 10^8 were tested by the authors without significantly changing the robustness of the results).

This method can be useful for finding extended asteroid families, but we must keep in mind that SLOAN fluxes are known with some uncertainties and that assigning spectral types to asteroids only based on the SLOAN fluxes may produce misleading results. Recently, Roig & Gil-Hutton (2006) have used the SLOAN data to compute albedos of the asteroids, discarding observations for which the percentile variation in the albedos errors was greater than 10% (and also did not satisfy other criterions, see Sect. 2.1 in Roig & Gil-Hutton 2006), and analyzed principal components to identify three objects in the Eunomia family region that were compatible with a V-type taxonomy: (21238) 1995 WV7 (which has recently been confirmed as a V-type object), (40521) 1999 RL95, and (66905) 1999 VC160. In Fig. 3 we show the location in the proper elements space of these asteroids.

We applied the extended metric of Bus & Binzel (2002a) to the Eunomia family by choosing the lowest numbered objects in the dynamical family that was also present in the SDSS catalog, (630) Euphemia (which is in the region of the S-type complex and satisfy Roig & Gil-Hutton (2006) criteria for a "good" SLOAN observation), and the results are given in Fig. 3. As in Nesvorný et al. (2004), we found that the extended metric is very useful for identifying family halos, i.e., populations of peripheral family members that are not joined by the rest of the family with the standard HCM method. In our case, we chose a cutoff of 205 m/s in the extended space, which was a compromise between lower values that did not identify any halos, and higher values that identified asteroids that are clearly members of other asteroid families.

What also can be seen in Fig. 3 is that asteroids in the Eunomia halo connect the orbital regions of (66905) and (21238). In particular, for the case of (21238), there seems to be a tail of asteroids originating from the Eunomia family and going toward the region of lower inclination where (21238) is present. We believe this is an indication of the link between (21238) and the Eunomia family, so we investigate this subject in the next section.

3. Dynamics in the region of (21238)

To discover the possible origin of (21238) 1995 WV7, we first need to understand the dynamics in the region. We start by identifying all mean-motion resonances up to order 6 involving the planets from Mars to Uranus, in the region of (21238): generally, three- and four-body resonances around (21238) are weak and of a high order. We will address this point later on, when discussing dynamical maps.

We then investigate the secular resonances in the region. By secular resonances we mean a commensurability between the

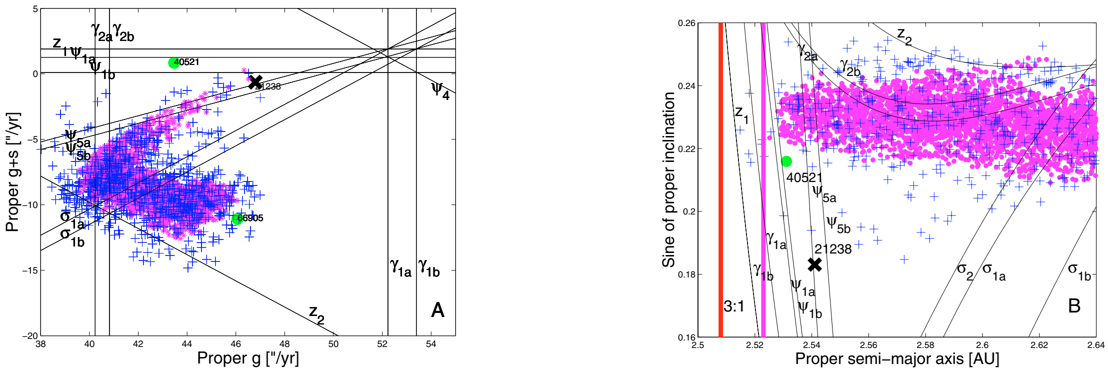

Fig. 4. In the *left panel* we show the location in the proper $(g, g+s)$ plane of the secular resonance in the region of (21238) that we identify in Table 1. The vertical lines display the resonances of perihelion, the horizontal lines the resonance of node and perihelion, the inclined lines the resonances of node and resonances involving other linear combinations of the frequencies g and s. The other symbols have the same meaning as in Fig. 3. In the *right panel* we show an $a-i$ projection of these resonances computed for the value of proper eccentricity of (21238), ($e_{21238} = 0.13345$).

frequency of variation in the longitudes of perihelia ($g_i = \dot{\varpi}_i$), in the longitudes of nodes ($s_i = \dot{\Omega}_i$) or both (the subscript i identifies the planet, i.e., 5 for Jupiter, 6 for Saturn, etc.; g and s with no subscript refer to the frequency of variation in the longitude of pericenter and node of the asteroid itself). The coefficients for such resonances must satisfy the two D'Alembert rules. Since there are many secular resonances in the region, to identify the ones most likely to have had a significant effect on the dynamical history of (21238), we only selected resonances involving the planets from Jupiter to Uranus[4] in the region of the Eunomia family, and we chose to work with resonance of an order lower than 4, or that involved harmonics of other powerful resonances.

We believe this approach is reasonable because here we are mostly interested in the dynamical history of (21238) and because, in general, while lower order resonances have a stronger effect on asteroid proper elements than higher order ones, resonances that involve harmonics of other powerful resonances may have a stronger effect than equivalent resonances of lower order. For instance, as investigated in Carruba et al. (2005), z_k[5] resonances are usually particularly effective in affecting asteroid proper elements, since their resonant argument involves harmonics of the powerful $\nu_6 = g - g_6$ resonance.

Table 1 reports the list of secular resonances involving Jupiter, Saturn, and Uranus that satisfy our criteria. In the first column we report the resonant argument, in the second the values of the asteroidal frequencies equivalent to the combination of the planetary frequencies present in the resonant argument (for instance in the $g-(-g_5+2g_6)$ resonance the asteroidal frequency g has to be equal to $2g_6 - g5 = 52.229''$/yr, etc.), and in the third column the name that we use in this paper to identify the resonances. Figure 4 displays the locations of such resonances, with the location of (21238) and of the members of the dynamical Eunomia family superimposed[6]. One common problem in visualizing secular resonances is that, contrary to mean-motion resonances, they have a complicated 3D structure in the space of proper $a-e-i$ elements, so that any 2D representation inevitably introduces distortions, and does not fully catch the complexity of the dynamics. This problem arises because the $a-e-i$ space is not the most appropriate space to study such resonances, which involve equalities between secular frequencies rather than mean motions. To overcome this problem, we prefer to first study these resonances in the most appropriate space, the proper $(g, g+s)$ plane, where their structure is given by vertical (perihelion resonances), horizontal (resonances of the generic form $g+s+...$), or inclined lines (resonances of nodes and other linear combinations of g and s), and then plot them in the usual proper $a-e$, $a-i$, $e-i$ planes. We believe that by using such an approach the web of secular resonances that crosses the main belt can be understood more easily (Knežević et al. 1991; Milani & Knežević 1993). As can be seen in Fig. 4, the Eunomia family shows a "curve" in the region of (21238) with members having higher values of proper g. This is caused by the proximity of the 3:1 mean motion resonance, whose effect is to increase the values of proper g (Knežević et al. 1991).

Table 1. Secular resonances in the region of the Eunomia family.

Resonant argument	Frequency ["/yr]	Names
g-type:		
$g-(-g_5+2g_6)$	52.229	γ_{1a}
$g-(-g_7+2g_6)$	53.393	γ_{1b}
g-type, 2nd harmonic:		
$2g-(-g_5+3g_6)$	40.236	γ_{2a}
$2g-(-g_7+3g_6)$	40.818	γ_{2b}
s-type:		
$(s-s_6)-(g_5-g_6)$	–50.331	σ_{1a}
$(s-s_6)-(g_7-g_6)$	–51.495	σ_{1b}
$s-2s_6+s_7$	–49.694	σ_2
(g+s)-type:		
$(g-g_5)+(s-s_7)$	1.261	ψ_{1a}
$(g-g_7)+(s-s_7)$	0.097	ψ_{1b}
$(g-g_6)+(s-s_6)$	1.898	ψ_2, z_1
(2g+s)-type, 2nd harmonic:		
$2(g-g_6)+(s-s_6)$	30.141	ψ_3, z_2
$2(g-g_6)+(s-s_7)$	53.490	ψ_4
(g+2s)-type, 2nd harmonic:		
$(g-g_5)+2(s-s_6)$	–48.433	ψ_5a
$(g-g_7)+2(s-s_6)$	–49.597	ψ_5a

[4] Including the Martian frequencies g_4 and s_4 increases the number of admissible resonant arguments by a factor 3, but the large majority of these resonances are too weak to have a significant dynamical effect on timescales larger than 10 Myr. For instance, we found that (21238) is currently inside two such resonances of arguments $s+2s_7-3s_4$ and $s-2s_6+s_4-g_5+g_4$, but it rapidly leaves the resonances when the Yarkovsky effect is considered (see Sect. 4).

[5] A z_k resonance is a resonant combination of the form $k(g-g_6)+s-s_6$.

[6] We only show family members for which the values of proper frequencies g and s were available in the file of synthetic proper elements of Milani & Knežević.

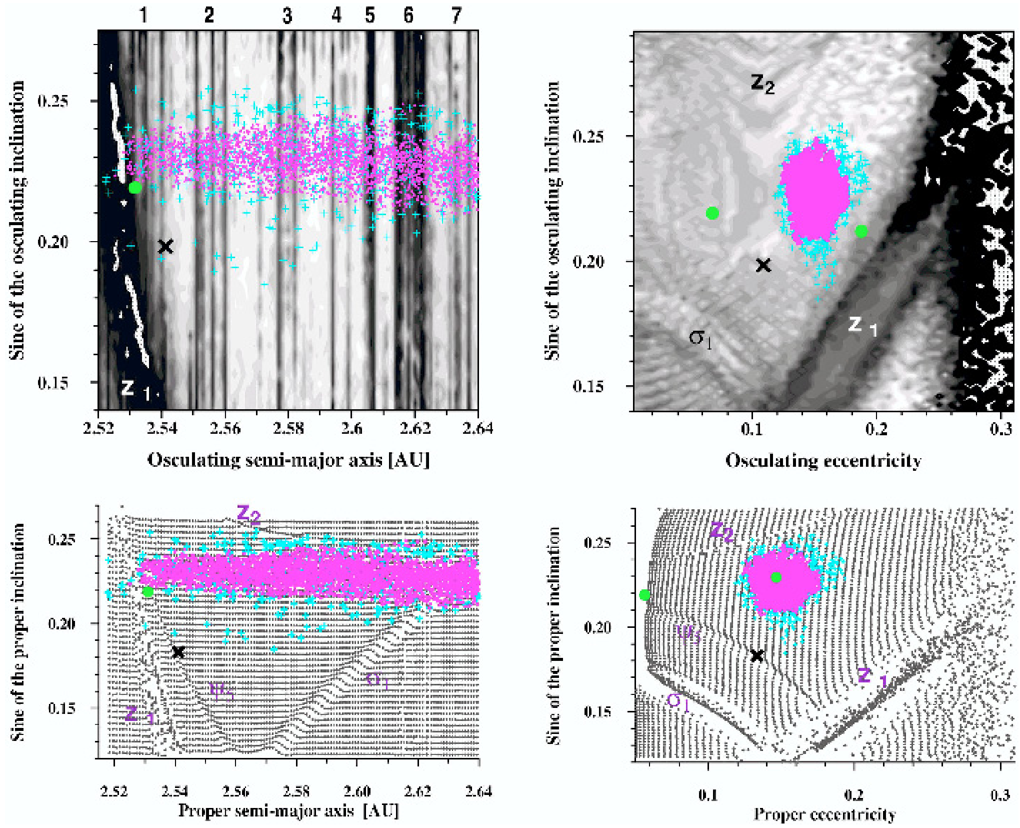

Fig. 5. In the *top panels* we show a dynamical map obtained with SAM of the $a - i$ and $e - i$ regions around (21238). In the *bottom panels* we display mean elements for the same initial conditions. Other symbols are the same as in Fig. 3.

To give an idea of how the structure of these resonances is much more complicated in the usual $a - e - i$ space, we also show their projections on the $a - i$ plane (Fig. 4b), obtained by best-fitting lines across asteroids having the same eccentricity as (21238) and frequencies compatible with those of the selected secular resonances. Note how the resonance topology is much more complicated in this plane and how it also represents a single value of the eccentricity, while resonances in Fig. 4a) display the dynamical behavior for all values of proper *e* and *i*.

As can be observed in Fig. 4 and in Table 1, there are several, generally weaker, secular resonances involving the g_7 frequency of Uranus associated with resonances involving the g_5 frequency. That these secular resonances are present with a multiplet structure is due to the fact that their resonant arguments differ only for the last frequencies (g_5 vs. g_7), and the difference between g_5 and g_7 is less than 1.1 ″/yr, which Milani & Knežević (1993) set as the limit for resolving two secular resonances in proper element space. The values of these two frequencies are so close because the perihelia of Jupiter and Uranus are in fact anti-aligned: $\varpi_5 - \varpi_7$ librates around 180° with a period of 1.1 Myr (Milani & Nobili 1984). This explains why several of the nonlinear secular resonances we observe in the main belt are overlapping.

Among the resonances we identified, the z_1 resonance, being a harmonic of the ν_6 resonance, can certainly be a natural candidate for providing diffusion in the proper element space of asteroids. In other cases, we may refer to the work of Nobili et al. (1989) and identify leading critical terms of the secular planetary theory that are also present in the resonant argument of the resonance of interest. Milani & Knežević (1993) identify the $(s - s_6) - (g_5 - g_6)$ resonance as a significant source of error in the determination of asteroid proper elements. Another strong resonance in the region is the $g - (-g_5 + 2g_6)$ resonance, which was identified by Milani & Knežević (1993) as a source of errors in the asteroid proper element determination and which also contains the strongest nonlinear forcing term $2g_6 - g_5$ of Nobili's secular planetary theory. Finally, a natural candidate for the process of diffusing asteroids from the Eunomia family to the location of (21238) might be the $(g - g_5) + 2(s - s_6)$ resonance, which crosses the family and passes very close to (21238) itself.

To confirm our hypothesis, we computed dynamical maps of the region of (21238) so as to select the most likely diffusion paths. We applied the Spectral Analysis Method (SAM) developed by Michtchenko et al. (2002): 4961 massless particles with initial test orbits distributed on a 121 × 41 grid in the (a, i) osculating plane and 5642 particles on a 62 × 91 grid in the (e, i) osculating plane were integrated over 4 Myr, accounting for planetary perturbations from Mars to Neptune. The initial osculating angular elements, Ω, ϖ, and λ of these test orbits were fixed at those of the (21238) object. The information on the spectral number used to characterize the chaoticity of the orbit, has been translated to a gray scale code and is shown in Fig. 5 (top).

The shading scale used in the dynamical maps in Fig. 5 (top) is related to the degree of stochasticity of the test orbits. The grey-scale goes as the logarithm of the number of lines in the Fourier spectra of the orbital elements, Michtchenko et al. (2002): the lighter regions in the dynamical map correspond to initial conditions of regular motion, and darker tones indicate increasingly chaotic motion. The domains where the test particles escape from the region within the time-interval of integration (~4 Myr) are hatched. The large-scale instabilities are originated by the 3:1 mean-motion resonance with Jupiter and the overlap of the resonances at high eccentricities.

Table 2. Mean motion resonances (up to fifth order in λ) for the region of (21238) 1995 WV7.

Mean-motion resonance	a [AU]	Group number
$n - 3n_5 - 2n_6 + 6n_7$	2.52563	1
$2n - 5n_5 - 4n_6 + 5n_6$	2.52858	
$n - 5n_5 + 3n_6 + 6n_6$	2.52981	
$6n - 5n_5 - 2n_4$	2.53674	
$n - 4n_5 + 3n_6 - n_7$	2.53573	
$2n - 6n_5 + n_6 - 2n_7$	2.53363	
$5n - 5n_6 - 2n_4$	2.54337	
$2n - 6n_5 + n_7$	2.54017	
$2n - 6n_5 - n_6 + 4n_7$	2.54675	2
$n - 4n_5 + 2n_6 + 2n_7$	2.54887	
$2n - 5n_5 - 2n_6$	2.55639	
$3n - 6n_6 - n_4$	2.55441	
$n - 3n_5 + 2n_6 - 5n_7$	2.55491	
$n - 2n_5 - 4n_6 + 5n_7$	2.55788	
$2n - 4n_5 - 5n_6 + 2n_7$	2.57967	3
$2n + n_5 - 3n_7 - n_4$	2.57806	
$n - 3n_5 + n_7$	2.58187	
$5n - 4n_6 - 2n_4$	2.59103	4
$n - 3n_5 - n_6 + 4n_7$	2.59562	
$4n - 5n_5 - n_4$	2.60143	5
$2n - 5n_5 - 3n_6 + 4n_7$	2.60574	
$n - 4n_5 + 4n_6 - 3n_7$	2.60644	
$n - 2n_5 - 2n_6$	2.61596	6
$2n - 6n_5 + n_6$	2.61824	
$n - 4n_5 + 3n_6$	2.62052	
$2n - 6n_5 + 3n_7$	2.62534	
$n - 2n_5 - 3n_6 + 3n_7$	2.63017	7
$2n - 6n_5 - n_6 + 6n_7$	2.63248	
$3n - 2n_5 - n_4$	2.63755	
$3n - 5n_6 - n_4$	2.63600	
$n - 4n_5 + 2n_6 + 3n_7$	2.63479	
$2n - 5n_5 - n_6 - n_7$	2.63575	

A relevant feature in Fig. 5 (top) is the occurrence of several vertical, thin stripes of chaotic motions, which are associated with mean-motion resonances with Jupiter, Saturn, Uranus, and Mars. Many of these resonances cut through the Eunomia family, and so we expect several family members to be in these resonances. We identify the main mean-motion resonances displayed in the dynamical map and their description is given in Table 2, where the first column reports the resonant argument (only including the mean motion terms, no secular frequencies), the second the value of the semi-major axis a where it is centered, and the third the name that we use in this article to identify groups of resonances.

In Fig. 5 (bottom) we show averaged dynamical maps of the neighborhood of the (21238) object, corresponding to the grids of initial osculating elements (averaged elements are calculated as the average of the osculating (or instantaneous) elements obtained during the integration). In the domains of the regular motion, the averaged orbital elements suffer continuous smooth variations when the initial conditions are gradually changed. In this way, the regions of regular motion are dominated by smoothed curves of points in the averaged maps. On the other hand, secular resonances induce large long-term variations in the orbital elements. The location of these resonances are clearly visible on the averaged maps due to the effect of exciting the asteroidal inclinations that reflects on the averaged orbital elements. Thus the averaged dynamical maps indicate the exact location of the secular resonances on the space of the proper elements and allow the estimation of their widths.

The proper elements of real objects can be easily plotted over the averaged dynamical maps, and consequently their distribution can be analyzed with respect to the web of resonances in the region under study. As can be seen from the maps, our hypothesis that the z_1, the $(s-s_6)-(g_5-g_6)$, and the $(g-g_5)+2(s-s_6)$ resonances are the most likely path for diffusion from the Eunomia family to the region of (21238) seems to be confirmed.

4. Yarkovsky evolution

The main objective of this work is to demonstrate that migration from the Eunomia family to the current orbital location of (21238) is possible, most likely via the interplay of the Yarkovsky effect with nonlinear secular resonances. For this purpose, we selected real asteroids currently in the Eunomia family or in the range of inclination covered by members of the dynamical family, whose orbits are inside i) the z_1 resonance, ii) the $(g-g_5)+2(s-2s_6)$ and the iii) $(s-s_6)-(g_5-g_6)$. We confirmed that those asteroids are in a resonant configuration by performing a 10 Myr simulation with SWIFT-MVSF.f, an integrator based on Wisdom & Holman (1991) symplectic mapping, modified to filter on line the orbital elements so as to eliminate all frequencies with periods shorter than 700 yr and by checking the behavior of the resonant arguments.

Once our targets were so selected, we performed a 1 Gyr integration with SWIFT-RMVSY.f, an integrator modified to account for the diurnal and seasonal version of the Yarkovsky effect by Mira Brož (1999). We created clones of the real asteroids with radii of 2.5 km, 3.0 km, 3.5 km, and 4 km. This was done because, with an absolute magnitude of 12.9, the derived radius of (21238) ranges from a minimum of 2.7 km to a maximum of 3.9 km, depending on the assumed albedo. The albedo may be as high as 0.42, like that of (4) Vesta, or as low as 0.21, like that of (1459) Magnya according to Tedesco et al. (2002). It is noteworthy, however, that more recent determinations give a value of 0.37 for (1459) Magnya (Delbó et al. 2006), which is the only other V-type asteroid with a known geometric albedo. A radius of about 4 km would also be obtained using the albedo of (15) Eunomia.

All orbital elements were computed in the coordinates system defined by the invariable plane of the Solar System, and we used the following thermal parameters, typical of basaltic objects covered by a regolith layer: $\rho_{\rm bulk} = 3500$ kg/m^3, $\rho_{\rm surface} = 1500$ kg/m^3, $K = 10^{-3}$ W/m^3/K, $C = 680$ J/kg/K, $A = 0.1$, and $\epsilon = 0.9$ (Farinella et al. 1998).

All asteroids were either prograde rotators with 0° obliquity (so that the diurnal Yarkovsky effect was anti-dissipative and the semi-major axis evolved towards higher values) or retrograde rotators (evolution towards smaller a) with 180° obliquity. Since our goal was to study diffusion in secular resonances, we did not consider re-orientations of spin axis via collisions or YORP (Čapek & Vokrouhlický 2004). Our simulated asteroids have constant obliquity and rotation periods. This assumption will not give realistic results for the timescale of the dynamical evolution of asteroids, but will allow them to evolve more efficiently in the secular resonances. The rotation periods were assigned assuming that they followed a Gaussian distribution with a peak for periods of six hours and truncated for periods less than 2 h or longer than 12 h.

In the next subsections we show the evolution of the test particles in the three main secular resonances that cross the region, starting with the $(g - g_5) + 2(s - s_6)$ resonance.

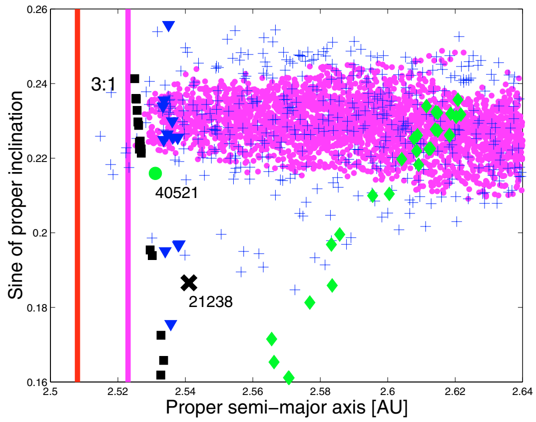

Fig. 6. The locations of the asteroids currently within ±0.1″/yr of the center of the $(g-g_5)+2(s-s_6)$ (blue triangles), of the z_1 (black squares), and of the $(s-s_6)-(g_5-g_6)$ (green diamonds) secular resonances in the proper $a-i$ space. For simplicity here we only show resonant asteroids with eccentricities in the same range as those of the Eunomia family members. The other symbols have the same meaning as in Fig. 4.

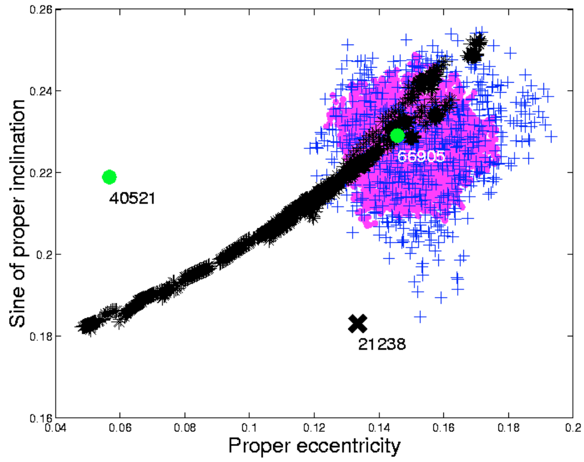

Fig. 7. The proper $e-i$ time evolution of clones of asteroids that evolved in the z_1 resonances (black asterisks). The other symbols are the same as in Fig. 3.

4.1. Evolution in the $(g-g_5)+2(s-s_6)$ secular resonance

The $(g-g_5)+2(s-s_6)$ secular resonance initially seemed the best candidate for explaining the origin of (21238). The asteroid is not currently inside the resonance, but is very close, and the resonance crosses the Eunomia family and points directly to the orbital position of (21238) (see Fig. 4). A natural scenario could have been for the asteroid to get captured in the resonance, evolve along it, and then leave the $(g-g_5)+2(s-s_6)$ resonance at values of proper i compatible with those of (21238) because either the Yarkovsky effect itself ejected the asteroid from the resonance or because the asteroid experienced a collision or a close encounter with another body (Carruba et al. 2003, 2007). Asteroids leave resonances because of these two mechanisms on very fast timescales. While the change in proper elements caused by a close encounter happens on timescales of hours, the Yarkovsky drift may take one asteroid out of resonance in timescales of ≃10 000–20 000 years.

To investigate this scenario, we identified all asteroids in the Eunomia region that have a value of the $g+2s$ frequency combination within ±0.1″/yr of the center of the resonance. Figure 6 shows the orbital locations of those objects in the proper $a-i$ spaces. We performed an integration with those objects without the Yarkovsky effect for 10 Myr and confirmed that they are currently inside the resonance.

Twelve of the resonant asteroids were members of the Eunomia family and were assigned prograde spin and sizes compatible with the possible size-range of (21238), as described in Sect. 4. Unfortunately, even though it is simple, this mechanism does not appear to be effective. Of the 48 particles we integrated, none remained in the resonance for longer than 120 Myr, with a maximal change of 0.008 in $\sin(i)$ (the difference in $\sin(i)$ between (21238) and the Eunomia family members with minimum inclination is of 0.02). We believe that these experiments show that, if (21238) originated in the Eunomia family, it most likely did not travel along this route.

4.2. Evolution in the z_1 secular resonance

We repeated the same analysis as for the asteroids in the $(g-g_5)+2(s-s_6)$ resonance for those in the z_1. Figure 6 shows the orbital locations of these objects in the $a-i$ plane. We identified 12 asteroids in the range of $e-i$ values compatible with those of members of the Eunomia family (none of the z_1 asteroids is a member of the family, so we took objects that could have easily reached the resonance by migration via the Yarkovsky effect) and generate 48 prograde clones with the characteristics discussed in Sect. 4. In contrast to the case of the $g-g_5+2(s-s_6)$ resonance, most of the simulated objects (85.4%) remained inside the resonance for the whole simulation. However, as can be seen in Fig. 7 (for simplicity, we do not show the orbital evolution of asteroids that left the resonance during the simulation), the problem with the evolution inside the z_1 resonance is that particles starting in the region of the Eunomia family cannot reach the orbital region of (21238) or (40521).

The time evolution in the proper $e-i$ plane[7] of the simulated particles shows that those particles can either reach the value of proper e or proper i of (21238) (or (40521)), but not both at the same time (it is interesting to notice how the values of proper e and i of (66905) are perfectly compatible with those of members of the Eunomia family. We elaborate on this point in Sect. 5).

We still need to verify the possibility that particles evolved in the z_1 resonance until reaching values of proper i compatible with those of (21238) or (40521). They then were ejected from resonance by one of the mechanisms discussed in Sect. 4.1 (either close encounters with massive asteroids or Yarkovsky drift) and interacted with some other resonance that caused the observed difference in proper e. To test this hypothesis we integrated 18 particles that had evolved in the z_1 resonance, had reached values of proper i compatible with those of the two asteroids, and were put outside the $z1$ resonance by shifting their osculating semi-major axis by 0.002 AU[8]. We then let these particles evolve until their proper semi-major axis reached values compatible with those of (40521) and (21238).

Unfortunately, none of the simulated particles experienced a change in proper e greater than 0.02 (the difference between the integrated particles initial e and those of (21238) and (40521) was ≃0.075). This was not surprising since our analysis and the dynamical maps we computed show that there are no strong

[7] We computed synthetic proper elements using the Knežević & Milani (2000) approach. See footnote 4 of Carruba et al. (2005) for more details on how to compute synthetic proper elements.

[8] This is a value compatible with the average displacement caused by a close encounter with a massive asteroid, as found in Carruba et al. (2007).

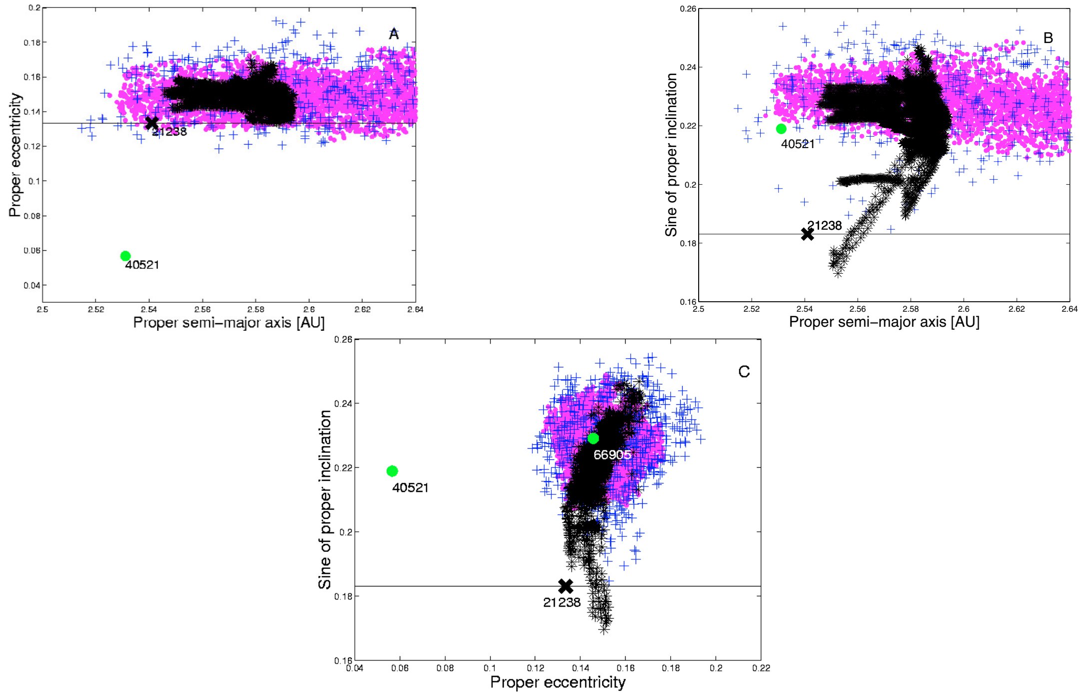

Fig. 8. Proper $a-e$, $a-i$, and $e-i$ projections of the Yarkovsky tracks of the 40 test particles we integrated (the other symbols are the same as in Fig. 3). The horizontal lines display the level of proper e (panel **A**)), $\sin(i)$ (panel **B**)), and $\sin(i)$ (panel **C**)) equal to those of (21238).

resonances between the z_1 resonance and the orbital location of (21238). Evolution in the z_1 secular resonance may have produced other, currently unknown V-type asteroids in the region. But, most likely, it did not produce (21238) and (40521).

4.3. Evolution in the $(s-s_6)-(g_5-g_6)$ secular resonance

After the cases of the $(g-g_5)+2(s-s_6)$ and of the z_1 resonances, we repeated the same analysis for the asteroids in the $(s-s_6)-(g_5-g_6)$ secular resonance. We identified 10 members of the Eunomia family currently inside this resonance and integrated 30 clones in the size range discussed in Sect. 4. Since evolution in the $(s-s_6)-(g_5-g_6)$ secular resonances appeared to be happening on very long timescales, we also integrated clones of 1 km in radius to "speed-up" the Yarkovsky diffusion, while remaining inside the resonance[9].

Figure 8 displays the time evolution in the proper $a-e$, $a-i$, and $e-i$ planes of the particles, after 800 Myr. As can be seen, particles that remained in the resonance (20% of the simulated particles) for the whole of the simulation did not change their eccentricity significantly, while evolving toward lower values of proper i. In particular, one of the 1 km radius particles evolved through values of proper i lower than that of (21238), while another particle of 2.5 km in radius reached a value of proper $\sin(i)$ of 0.189 at the end of the simulation, while the value of proper eccentricity remained constant at 0.139, very similar to the values of (21238) of 0.183 and 0.1334, respectively.

We believe that these simulations prove that migration in the $(s-s_6)-(g_5-g_6)$ resonance (or in another of the overlapping σ_1 node resonances involving combinations of the Uranus frequency g_7 listed in Table 1) from the Eunomia family may have produced the current orbital configuration of (21238) (and of other objects in the "halo" of the Eunomia family at low proper i identified with the color metric of Sect. 2.3). In our scenario, members of the Eunomia family are captured by the σ_1 resonances and evolve to lower values of proper i. Once the family members reach the inclination of (21238), they are ejected from the resonance by one of the mechanisms described in Sect. 4.1 and then evolved via a simple Yarkovsky effect, until reaching the value of proper semi-major axis of (21238).

To confirm this scenario further, we performed two numerical experiments. First, we computed a dynamical map of the Eunomia region (same methodology as in Sect. 3) in the $e-i$ plane for the value of semi-major axis at which, in the $a-i$ plane, the line of $i = i_{21238}$ crosses the location of the σ_1 complex (i.e., the location for which, in our scenario, (21238) left the σ_1 resonances and started evolving as a free-drifting object via Yarkovsky effect, $a = 2.6$ AU). Figure 9 shows how the σ_1 resonances' complex for that value of proper a crosses the Eunomia family and connects it to the orbital location in proper $e-i$ of (21238).

To simulate asteroids recently ejected from the σ_1 resonances, we took asteroids currently in the σ_1 resonances, having values of proper e and $\sin(i)$ to within ± 0.015 those of (21238), and subtracted 0.002 AU from their initial osculating a, so as to put these asteroids out of resonance. We created 28 retrograde clones of the 7 asteroids thus identified, and let them evolve until reaching values of semi-major axis equal to those of (21238). Of the 28 objects, only one interacted with the $n-3n_5+n_7$ mean motion resonance and had its eccentricity decreased by 0.03, while all the other objects maintained their initial values of proper e

[9] While 1 km bodies are certainly smaller than (21238), the advantage of using bodies this size is that their diffusion as caused by the Yarkovsky effect is much faster than for objects of 2.5 or 4 km in radius. If these objects can remain inside the resonance, then it is very likely that a larger object will not be ejected from the $(s-s_6)-(g_5-g_6)$ secular resonance either. But while 1 km radius objects will diffuse from the region of Eunomia to the orbit of (21238) in a few days of computer time, the computer time required for the diffusion of larger bodies is considerably longer. To test that diffusion in the $(s-s_6)-(g_5-g_6)$ secular resonance was a viable option, we therefore decided to also use smaller bodies.

Table 3. The total time T_{total} needed to go from the Eunomia family to the orbital location of (21238) as a function of the asteroid size.

Radius [km]	d[sin (*i*)]/d*t* [10^{-5} Myr^{-1}]	$T_{\sin(i)}$ [Gyr]	T_{a} [Gyr]	T_{total} [Gyr]
2.5	3.50	1.25	1.35	2.60
3.0	3.10	1.40	1.60	3.00
3.5	2.50	1.75	1.90	3.65
4.0	2.20	2.00	2.10	4.10

and *i* to within ±0.01. The average times T_{a} needed to reach the orbital location of (21238) as a function of asteroid radius are given in Table 3. This experiment further confirms our two-step scenario in which (21238) originated as a former Eunomia family member, evolved in the σ_1 resonances until reaching its current value of proper *i*, and then freely drifted via the Yarkovsky effect.

What timescales are required to produce the current orbital location of (21238)? As previously discussed, the time-span of our simulation was not long enough to allow the largest particles drifting in the σ_1 resonances to reach levels of proper *i* comparable to that of (21238). We are currently extending our simulations, but while waiting for those results, we performed a numerical experiment to compute the average rate of change in proper sin (*i*) as a function of the asteroid size.

We selected 19 asteroids in the σ_1 resonance in the region between the Eunomia family and (21238) proper *i* and generated 76 retrograde clones with the sizes and properties discussed in Sect. 4. We integrated those objects for 250 Myr and then computed the averaged change in proper sin (*i*) per Myr for asteroids in the σ_1 resonances. Table 3 shows our results, as well as our estimates for the time needed to cover the distances between the average value of proper *i* of Eunomia family members and (21238) ($\Delta \sin(i) = 0.044$). Our results suggest that the minimal time required to diffuse from the Eunomia family to the orbital location of (21238) varies between 2.6 Gyr for $R = 2.5$ km objects to 4.1 Gyr for $R = 4$ km asteroids. While the timescales for migration of an object with a radius up to 3.5 km agrees with the estimates for the Eunomia family age found by Nesvorný et al. (2004) ((2.5 ± 1.0) Gyr), higher estimates for the size of (21238) would result in migration times that are greater than the family age. If (21238) is a large body, it is possible that it might have originated in a collision that preceded the one that formed the current Eunomia family. The repercussions of this hypothesis will be discussed in the conclusions.

We also believe that it is quite unlikely that (21238) originated as a member of other families in the region (see Fig. 1), the Adeona, the Maria, and the Renate families. The Adeona family is a C-type family, and it is not a likely source for a basaltic object. Maria and Renate are S-type families. We have no hint that the parent body that originated these families was a differentiated object, while there are several studies that suggest this possibility for the parent body of (15) Eunomia (Reed et al. 1997; Nathues et al. 2005).

Even assuming that the parent bodies of these two families were differentiated, dynamically it is quite unlikely that (21238) originated as a member of one of this families. The only mechanism that could possibly explain the current value of (21238) inclination is, according to our study, evolution in the $(s - s_6) - (g_5 - g_6)$ resonance. The Maria family is not crossed by this resonance, while a member of the Renate family would have i) a value of the proper eccentricity that is incompatible with (21238) (the evolution in the $(s - s_6) - (g_5 - g_6)$ resonance

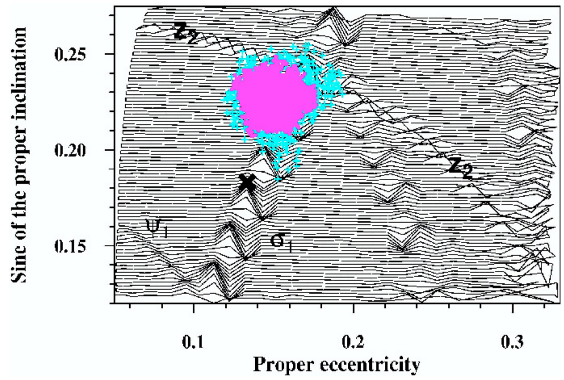

Fig. 9. A dynamical map in the $e - i$ plane computed for $a = 2.6$ AU for the region of (21238).

preserves proper eccentricity), and ii) it would have to cross the whole of the Eunomia family in inclination to get to the current orbit of (21238) (see Fig. 1b).

For these reasons, we think it very unlikely that (21238) originated as a member of any family in the region either than Eunomia.

5. Origin of (40521)1999 RL95 and (66905) 1999 VC160

In the previous section we discussed the possible origin of (21238) as a former member of the Eunomia family. Two other asteroids were identified by Roig & Gil-Hutton (2006) as having SLOAN albedos compatible with a V-type taxonomy: (40521) 1999 RL95 and (66905) 1999 VC160. In this section we investigate whether these objects, too, may have originated as former Eunomia family members.

We begin by analyzing the case of (66905). As already shown in Figs. 3 and 7, the only difference between (66905) and Eunomia family members is in proper semi-major axis, while the proper *e* and *i* are compatible with family membership. Can a simple evolution via the Yarkovsky effect explain the origin of this asteroid? To check this hypothesis we computed the location of the main mean-motion and secular resonances in the region of (66905) and find no important secular resonances, while the most important mean-motion resonance is the 8:3 resonance with Jupiter, which determines the right edge of the Eunomia family (Fig. 3).

Can asteroids evolving with the Yarkovsky effect pass through the 8:3 while preserving their proper *e* and *i*? Since the spectral type of (66905) has not yet been confirmed, we preferred not to perform numerical simulations with symplectic integrators at this stage of our knowledge; but in a previous work on the Yarkovsky evolution of the Adeona family, we did observe particle passing through such resonances without suffering changes in proper *e* and *i* (Carruba et al. 2003, Fig. 7). We therefore believe that the hypothesis of (66905) being a former member of the Eunomia family is quite reasonable.

Timescales for the drifting of (66905) to its current location are also compatible with those of (21238). When assuming a maximum drift rate (no reorientations, 0° obliquity, and a constant period of rotation of 5 h) and using Vokrouhlický (1999) model of Yarkovsky effect for spherical objects, the time needed to cover the distance between (66905) ($a = 2.74627$ AU) and the nearest Eunomia member ($a = 2.70625$ AU) varies between 0.5 Gyr for $R = 1.3$ km and 0.8 Gyr for $R = 1.8$ km (the minimum and maximum radii of (66905) using the albedos described

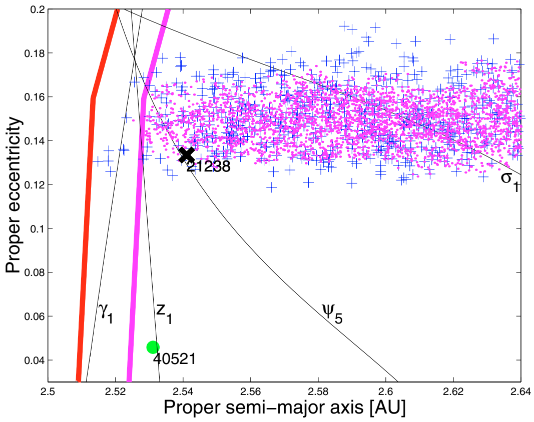

Fig. 10. The location of the four main secular resonances in the region of (40521), projected in the $a - e$ plane.

in Sect. 4 and its absolute magnitude of 14.5). These times may of course be longer if reorientations are considered and if we have taken an initial starting point for the drifting process at lower values of proper *a*.

More complicated is to infer the origin of (40521). In contrast to the case of (21238), which only differs from members of the Eunomia family because of its proper inclination, the main difference between (40521) and members of the Eunomia family lies in the proper eccentricity (see Fig. 3). An evolutionary mechanism able to explain its current value of proper *e* should therefore focus on resonances that only act on eccentricity, such as the pericenter secular resonances, rather than on node resonances as for (21238).

Figure 10 shows a $a - e$ projection of the main secular resonances in the region of (40521), computed for the value of inclination of (40521) (for simplicity, we only show resonances that involve frequencies of Jupiter and Saturn). Of the four resonances in the region, the $(g - g_5) + 2(s - s_6)$, the z_1, and the $(s - s_6) - (g_5 - g_6)$ resonances cannot have caused the current orbital configuration of (40521) for reasons explained in Sect. 4. The only possible evolutionary path left is evolution in the γ_1 $(g-(-g_5+2g_6))$ resonance, which, being a resonance of pericenter, could have reduced the initial value of (40251) eccentricity, while preserving its inclination.

We believe this is a reasonable explanation, but again, since the taxonomic type of (40521) has not been confirmed yet, we preferred not to perform computationally expensive numerical simulation for this object.

6. Conclusions

In this work we have studied possible migration routes from the orbital region of the Eunomia family to the current orbital locations of a recently identified V-type object in the region, (21238) 1995 WV7, and of two other asteroids whose SLOAN albedos are compatible with V-type classification: (40521) 1999 RL95 and (66905) VC160 (Roig & Gil-Hutton 2006). For this purpose we:

- Performed a mineralogical analysis of asteroids in the region for which a taxonomic classification was available at the time we wrote this article.
- Identified the Eunomia family using i) the hierarchical clustering method of Zappalá et al. (1990, 1995) and ii) the extended metric in color space of Bus & Binzel (2002a). The second method allowed us to identify "halo" objects (i.e., populations of peripheral family members that were not joined with the rest of the family with the standard HCM method) that connected the orbital locations of (21238) and (66905) to the region of the Eunomia family, giving a first hint of the possible origin of these objects.
- Conducted a dynamical analysis of the Eunomia region and identified the main mean-motion and secular resonances with numerical and analytical tools.
- Performed simulations that included the Yarkovsky effect: (21238) might have evolved to its current location via the interplay of the Yarkovsky effect and the $(s - s_6) - (g_5 - g_6)$ resonance.
- Identified possible migration paths from the Eunomia family to the current orbits of (40521) and (66905).

A question that naturally arises at this point in our work is the following: if Eunomia was a differentiated object and had a basaltic crust, should there not be many other V-type objects in the region than just the one, possibly three that we know of?

A simple answer to this question could be that these other asteroids might not yet have been identified as V-type objects. A more intriguing possibility is that the V-type asteroids we currently observe in the region might be a few of the last survivors of a collision that preceded in time the one that formed the current Eunomia family.

We believe this is a reasonable possibility because i) we know that Eunomia is currently compatible with a differentiated object whose crust has been stripped, but whose core has possibly not been exposed, due to the lack of M-type objects in the region (Nathues et al. 2005), and ii) the timescales for the diffusion from the Eunomia region to the orbital locations of (21238), (40521), and (66905) are very long, possibly even longer than the (2.5 ± 1.0) Gyr that Nesvorný et al. (2004) gives as an estimate of the age of the Eunomia family. Can other objects have already diffused away via the interaction with very powerful mean motion (3:1 and 5:2 resonances with Jupiter, for example), or secular resonances (the z_1 and the $g-(-2g_5+3g_6)$, among others) and no longer be recognizable as former members of the Eunomia family?

If this hypothesis is confirmed, (15) Eunomia could be the third parent body of V-type objects after (4) Vesta and (1459) Magnya, opening interesting perspectives on the origin of basaltic material in the asteroid belt.

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Note: After this paper was accepted for publication another work on the origin of (21238) and (40521) was submitted to Icarus (ad astro-ph) by Roig et al. In their paper the authors i) observed (40521) and confirmed its status as a V-type object and ii) performed simulations with particles crossing the 3:1 resonances and computed the probability of an asteroid of diameter D to cross the 3:1 resonance. Their results indicate that a body of the size of (21238) has a low probability ($P < 10\%$) to safely cross this resonance in the timescales associated with the estimated maximum age of the Vesta family ($T > 3.5$ Gyr, Bogard & Garrison 2003).

At present, the origin of (21238) is still uncertain. This asteroid might be a lucky survivor of the 3:1 resonance crossing or, as suggested in this paper, one of the last remnants of the long-lost basaltic crust of the parent body of the Eunomia family. If other V-type objects will be identified in the region of the Eunomia family in the next years, more than the numbers possibly produced with the mechanism proposed by Roig et al. (2007), this could be a significant argument in favour of our hypothesis. We encourage the observing community to search for other possible V-type asteroids in this region of space.

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