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On the oldest asteroid families in the main belt

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ABSTRACT

Asteroid families are groups of minor bodies produced by high-velocity collisions. After the initial dispersions of the parent bodies fragments, their orbits evolve because of several gravitational and non-gravitational effects, such as diffusion in mean-motion resonances, Yarkovsky and Yarkovsky–O'Keefe–Radzievskii–Paddack (YORP) effects, close encounters of collisions, etc. The subsequent dynamical evolution of asteroid family members may cause some of the original fragments to travel beyond the conventional limits of the asteroid family. Eventually, the whole family will dynamically disperse and no longer be recognizable. A natural question that may arise concerns the time-scales for dispersion of large families. In particular, what is the oldest still recognizable family in the main belt? Are there any families that may date from the late stages of the late heavy bombardment and that could provide clues on our understanding of the primitive Solar system? In this work, we investigate the dynamical stability of seven of the allegedly oldest families in the asteroid main belt. Our results show that none of the seven studied families has a nominally mean estimated age older than 2.7 Gyr, assuming standard values for the parameters describing the strength of the Yarkovsky force. Most 'paleo-families' that formed between 2.7 and 3.8 Gyr would be characterized by a very shallow size–frequency distribution, and could be recognizable only if located in a dynamically less active region (such as that of the Koronis family). V-type asteroids in the central main belt could be compatible with a formation from a paleo-Eunomia family.

Key words: celestial mechanics – minor planets, asteroids: general.

1 INTRODUCTION

Asteroid families are born out of collisions. They 'die' when the fragments formed in the collisional event disperse so far because of gravitational or non-gravitational forces that the family is no longer recognizable as a group. The time needed to disperse small groups has been the subject of several studies (from our group, see for instance Carruba 2010a; Carruba, Machuca & Gasparino 2011; Carruba et al. 2015). Less attention has been given to the dispersion of larger families. Recent studies (Brasil et al. 2015) suggested that no family could have likely survived the late heavy bombardment (LHB hereafter, at least 3.8 Gyr ago), in the jumping Jupiter scenario, which set an upper limit on the maximum possible age of any asteroid family. In this work, we focus our attention on the families whose estimated age, according to Brož et al. (2013) could possibly date from just after the LHB, and whose existence, if confirmed, could provide precious clues on the early stages of our Solar system.

Brož et al. (2013) identified 12 families whose age estimate might have been compatible with an origin during the LHB, or just after the Maria, Eunomia, Koronis, Themis, Hygiea, Meliboea, Ursula, Fringilla, Alauda, Sylvia, Camilla, and Hermione families. The Sylvia family and the proposed long-lost groups around Camilla and Hermione in the Cybele region were recently studied in Carruba et al. (2015), and will not be treated in detail here. That work found that, while all asteroids in the Cybele region were most likely lost during the jumping Jupiter phase of the model of planetary migration of Nesvorný, Vokrouhlický & Morbidelli (2013), some of the largest fragments ($D > 5$ km, with D the body diameter) of a hypothetical post-LHB Sylvia family may have remained in the Cybele region, but the identification of these groups could be difficult. Due to local dynamics, any Camilla and Hermione families would disperse in time-scales of the order of 1.5 Gyr. The Fringilla family is a rather small group (134 members, according to Nesvorný, Brož & Carruba 2015) in the outer main belt. Since we are already studying the larger Themis, Meliboea, Alauda, and Ursula families in the outer main belt, and since the group is not large enough for the techniques

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used in this work, we will not further investigate this family in this paper. The Hygiea family was studied at length in Carruba et al. (2014a), that found a maximum possible age of 3.6 Gyr, just a bit younger than the minimum currently believed epoch of the last stages of the LHB, i.e. 3.8 Gyr (Bottke et al. 2012; also the age of the Hygiea family should be most likely younger than 3.6 Gyr, because of the long-term effect of close encounters with 10 Hygiea and of the stochastic Yarkovsky–O'Keefe–Radzievskii–Paddack (YORP) effect of Bottke et al. 2015, this last effect not considered in Carruba et al. 2014a). Age estimates for the other families listed in Brož et al. (2013) are however known with substantial uncertainty, and were obtained before Bottke et al. (2015) modelled the so-called stochastic YORP effect, in which the shapes of asteroids changes between YORP cycles, and whose effect is generally to reduce the estimates of the given asteroid family age. Understanding which, if any, of the proposed 'Brož seven' oldest groups (Maria, Eunomia, Koronis, Themis, Meliboea, Ursula, Alauda) could have survived since the LHB, and how, is the main goal of this work.

This paper is so divided: in Section 2, we identified the seven 'Brož' families in a new space of proper elements and Sloan Digital Sky Survey-Moving Object Catalog data, fourth release (SDSS-MOC4) *gri* slope and $z' - i'$ colours, and use the method of Yarkovsky isolines to obtain estimates of maximum possible ages of these groups. In Section 3, we use Monte Carlo methods (see Carruba et al. 2015) to obtain refined estimates of the family age and ejection velocity parameters of the same families. Section 4 deals with the dynamical evolution and dispersion times of fictitious simulated 'Brož' groups since the latest phases of the LHB, when the stochastic YORP effect (Bottke et al. 2015) and past changes in the solar luminosity (Carruba et al. 2015) are accounted for. Finally, in the last section, we present our conclusions.

2 FAMILY IDENTIFICATION

In order to obtain age estimates of the seven Brož families, we first need to obtain good memberships of these groups. Any method used should aim to reduce the number of possible interlopers, objects that may be part of the dynamical family, but have taxonomical properties inconsistent with that of the majority of the members. DeMeo & Carry (2013) recently introduced a new classification method, based on the Bus-DeMeo taxonomic system, that employs SDSS-MOC4 (Ivezić et al. 2002) *gri* slope and $z' - i'$ colours. In that article, the authors used the photometric data obtained in the five filters u', g', r', i', and z', from 0.3 to 1.0 µ*m*, to obtain values of $z' - i'$ colours and spectral slopes over the g', r', and i' reflectance values, that were then used to assign to each asteroid a likely spectral type. Since the authors were interested in dealing with a complete sample, they limited their analysis to asteroids with absolute magnitude H higher than 15.3, which roughly corresponds to asteroids with diameters larger than 5 km, and for which the SDSS-MOC4 data set is supposed to be complete. Since Carruba et al. (2015) showed that the vast majority of asteroids that could survive 3.8 Gyr of dynamical evolution in the post-LHB scenario should have diameters larger than 5 km, we believe that this choice of limit in H could also be suitable for this research. For completeness, we also included asteroids with $H < 12.00$ with known spectral types from the planetary data system (Neese 2010) that are not part of SDSS-MOC4. These objects were assigned values of the *gri* slope and $z' - i'$ colours at the centre of the range of those of each given class. We refer the reader to DeMeo & Carry (2013) and Carruba et al. (2014a) for more details on the procedure to obtain *gri* slope and $z' - i'$ colours, and on how to assign asteroids spectral classes based on these data.

Once a complete set of data with proper elements, obtained from the AstDys site (http://hamilton.dm.unipi.it/cgi-bin/astdys/astibo, accessed on 2015 April 4th (Knežević & Milani 2003), taxonomical and SDSS-MOC4 data on *gri* slope and $z' - i'$ colours has been computed for asteroids in each given asteroid family region, family membership is obtained using the hierarchical clustering method (HCM) of Bendjoya & Zappalá (2002) in an extended domain of proper elements and *gri* slope and $z' - i'$ colours, where distances were computed using the new distance metric:

$$d_{\rm md} = \sqrt{d^2 + C_{\rm SPV}[(f_{\rm gri}\Delta gri)^2 + (\Delta(i - z))^2]}, \tag{1}$$

where d is the standard distance metrics in proper element domain defined in Zappalá et al. (1995) as

$$d = na\sqrt{k_1(\frac{\Delta a}{a})^2 + k_2(\Delta e)^2 + k_3(\Delta \sin(i))^2}, \tag{2}$$

where n is the asteroid mean motion; Δx the difference in proper a, e, and $\sin(i)$; and k_1, k_2, k_3 are weighting factors, defined as $k_1 = 5/4$, $k_2 = 2$, $k_3 = 2$ in Zappalá et al. (1990, 1995). Δgri and $\Delta(i - z)$ are difference between two neighbouring asteroids *gri* slopes and $z' - i'$ colours, $C_{\rm SPV}$ is a constant equal to 10^6 (see also Carruba et al. 2013, for a discussion on the choice of this constant) and $f_{\rm gri} = 0.027$ is a normalization factor to account for differences among the mean values of differences in *gri* slope and $z' - i'$ colours (different values of $f_{\rm gri}$ in the range 0.05–0.001 have been used without substantially affecting the output of the method). We assigned families to their regions, defined as in Brož et al. (2013) as the central main belt, the pristine region, the outer main belt and the outer highly inclined region, and compute proper elements and *gri* slope and $z' - i'$ colours for all asteroids in each given region. We then computed nominal distance cutoff and stalactite diagrams with the standard techniques described in Carruba (2010b), for all the seven Brož families, and then assigned values of diameters and geometric albedos from the *WISE* catalogue (Wright et al. 2010) to family members for which this information is available [other objects were assigned the values of geometric albedo of the largest object in the family, and diameters computed using equation (1) in Carruba et al. 2003]. Finally the method of the Yarkovsky isolines (see also Carruba et al. 2013) is applied to obtain an estimate of the maximum possible age of each given family. In the next subsection, we will discuss in detail the method for families in the outer main belt, results are similar for other regions.

2.1 The outer main belt: the themis, meliboea, and ursula families

The outer main belt is defined in Nesvorný et al. (2015) as the region between the 7J:-3A and 2J:-1A mean-motion resonances and $\sin(i) < 0.3$. Three possible old C-complex families have been proposed in this region: the Themis, Meliboea, and Ursula groups. We identified 5472 asteroids with either taxonomical or SDSS-MOC4 information in the area, 3524 of which with data in the *WISE* data set, and 2896 (82.2 per cent) with $p_V < 0.15$. The value of the minimal distance cutoff d_0 was of 157.5 m s^{-1} and the minimal number of objects to have a group statistically significant was 25.

Fig. 1, panel A, displays a stalactite diagram for this region. The families of Themis, Meliboea, and Ursula were all visible at the nominal distance cutoff d_0, but not for lower values of d. 137 Meliboea merges with the local background at $d = 300$ m s^{-1}. The family of 375 Ursula merges with Eos at cutoff of 250 m s^{-1}, and with other minor groups at $d = 225$ m s^{-1}, so we choose to work

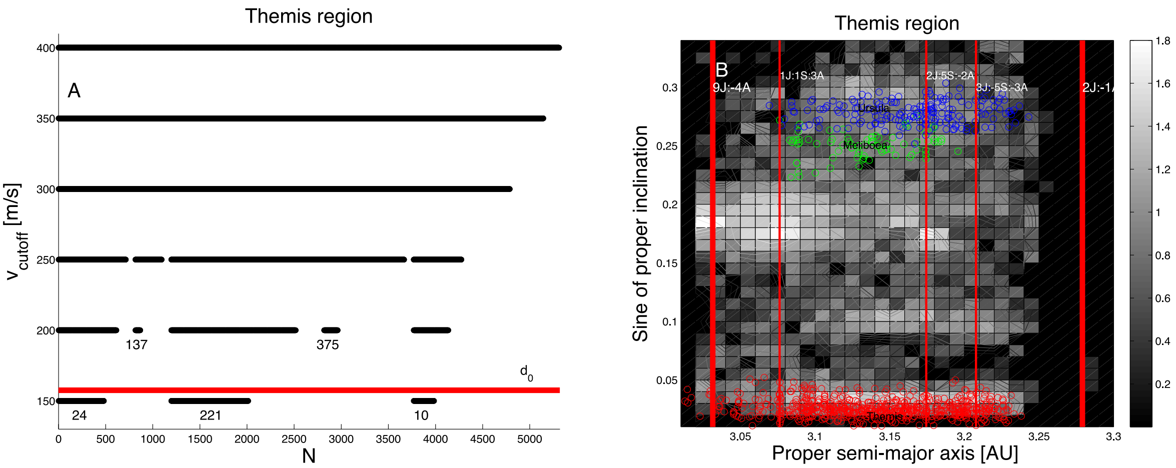

Figure 1. Panel A: stalactite diagram for the 5472 asteroids in the Themis region. Asteroids belonging to a family are identified by black dots. Panel B: contour plot of number density of asteroids in the (a, sin (i)) plane. Red, green and blue circles show the location of members of the Themis, Meliboea, and Ursula families, respectively.

with a cutoff of 220 m s^{-1}. Other important families in the region were those of 221 Eos and 10 Hygiea. Panel B of Fig. 1 displays a contour plot of number density of asteroids in the (a, sin (i)) plane. Whither tones are associated with higher values of local number density. For our grid in this domain, we used 30 steps of 0.01 au in a, starting from $a = 3.0$ au, and 34 steps of 0.01 in sin (i), starting from sin (i) = 0.0. The members of the identified Themis, Meliboea, and Ursula families, after taxonomical interlopers were removed (there were none in these cases), are shown as red, green, and blue circles, respectively.

Finally, we also apply the method of Yarkovsky isolines (Carruba et al. 2013) to the Themis, Meliboea, and Ursula families, using standard values of the parameters of this force for C-type groups from Brož et al. (2013), table 2. Results are shown in Fig. 2 for the Themis family. The red and blue lines are the expected displacement of family members over 3.8 and 4.6 Gyr because of the Yarkovsky effect and close encounters with massive asteroids, assumed equal to 0.01 au for simplicity (Carruba et al. 2014a). All asteroids were assumed to be initially at the family barycentre. This method yields maximum ages of 4.6 Gyr for the three Themis, Meliboea, and Ursula families. Information on number of confirmed members and interlopers is given in Table 1, among other quantities.

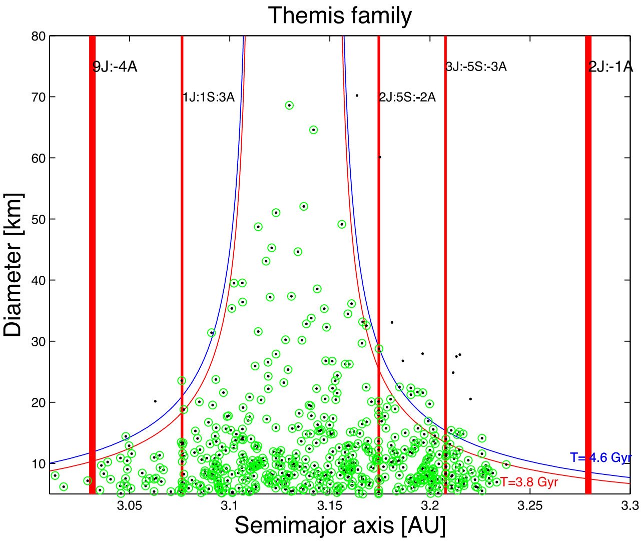

Figure 2. Yarkovsky isolines age estimates for the Themis family. Black dots identify members of the dynamical group without the taxonomical interlopers, and green circles show the position of members that are not dynamical interlopers. Vertical red lines display the location of mean-motion resonances, the red and blue lines displays isolines of displacement from the family barycentre due to Yarkovsky effect and close encounters with massive asteroids over 3.8 and 4.6 Gyr, respectively.

3 CHRONOLOGY

Monte Carlo methods to obtain estimates of the family age and ejection velocity parameters were pioneered by Vokrouhlický et al. (2006a,b,c) for the Eos and other asteroid groups. They were recently modified to account for the 'stochastic' version of the YORP effect (Bottke et al. 2015), and for changes in the past values of solar luminosity (Vokrouhlický et al. 2006a) for a study of dynamical groups in the Cybele region (Carruba et al. 2015). Age estimates obtained including the stochastic YORP effect in Carruba et al. (2015) were (i) of better quality with respect those obtained with the static version of YORP for old families, in terms of confidence level, and (ii) tend to produce younger age estimates. We refer the reader to Bottke et al. (2015) and Carruba et al. (2015) for a more in depth description of the method. Essentially, the semimajor axis distribution of various fictitious families is evolved under the influence of the Yarkovsky, both diurnal and seasonal versions, and YORP effect and occasionally other effects such as close encounters with massive asteroids (Carruba et al. 2014a) or changes in past solar luminosity values (Carruba et al. 2015). This method, however, ignores the effect of planetary perturbations. The newly obtained distributions of a C-target function computed with the relationship:

$$0.2H = \log_{10}(\Delta a/C), \quad (3)$$

are then compared to the current C distribution of real family members using a χ^2-like variable $\psi_{\Delta C}$ (Vokrouhlický et al. 2006a,b,c), whose minimum value is associated with the best-fitted solution.

We applied this method to six out of the seven 'Brož' families. For the case of the Maria family, since this group was significantly depleted at lower semimajor axis by interaction with the 3J:-1A mean-motion resonance, the number of remaining intervals in the C-target function was too small to allow for a precise determination

Table 1. Orbital region, spectral complexes, number of asteroids in the orbital region, distance cutoff d_0, number of taxonomical interlopers, of dynamical interlopers, confirmed members, and maximum age estimates, inferred by Yarkovsky isolines, of the 'Brož' seven families.

Family name	Orbital region	Number of asteroids	d_0 (m s^{-1})	Spectral complex	Number of tax. interlopers	Number of dyn. interlopers	Number of confirmed members	Maximum age estimate (Gyr)
Eunomia	Central mb	1416	155	S	33	1	1101	3.8
Maria	Central mb	1416	155	S	16	1	386	3.8
Koronis	Pristine zone	1015	135	S	18	1	502	4.6
Themis	Outer mb	5472	220	CX	0	10	642	4.6
Meliboea	Outer mb	5472	220	CX	0	4	78	4.6
Ursula	Outer mb	5472	220	CX	0	11	172	4.6
Alauda	H I Outer mb	286	250	CX	1	23	122	4.6

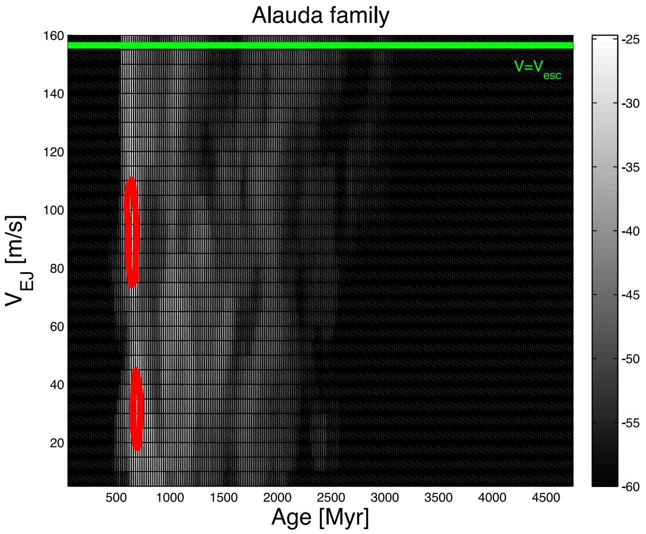

Figure 3. Target function $\psi_{\Delta C}$ values in the (Age, V_{EJ}) plane for Alauda family. The horizontal green line display the value of the estimated escape velocity from the parent body. The red lines display the contour level of $\psi_{\Delta C}$ associated with a 1σ probability that the simulated and real distribution were compatible.

of the family age. Fig. 3 displays $\psi_{\Delta C}$ values in the (Age, V_{EJ}) plane for Alauda family. Values of the V_{EJ} parameter, that describes the spread in the terminal ejection velocities (Vokrouhlický et al. 2006a,b,c), tend to be lower than the estimated escape velocity from the parent body (Bottke et al. 2015), 156.5 m s^{-1} for the case of the Alauda family. To estimate nominal values of the uncertainties associated with our estimate of the age and the V_{EJ} parameter, here we used the approach first described in Vokrouhlický et al. (2006a,b,c). First, we computed the number of degrees of freedom of the χ^2-like variable, given by the number of intervals in the C distribution with more than 10 asteroids (we require a minimum number of 10 asteroid per C interval so as to avoid the problems associated with dividing by small number when computing $\psi_{\Delta C}$), minus 2, the number of parameters estimated from the distribution. Then, assuming that the $\psi_{\Delta C}$ probability distribution is given by an incomplete gamma function of arguments $\psi_{\Delta C}$ and the number of degrees of freedom, we computed the value of $\psi_{\Delta C}$ associated with a 1σ probability (or 68.3 per cent) that the simulated and real distribution were compatible (Press et al. 2001).[1]

Table 2. Estimated age and ejection velocity parameter from Monte Carlo chronology for six 'Brož' families.

Name	Age (Myr)	V_{EJ} (m s^{-1})	$\psi_{\Delta C}$
Eunomia	2020^{+650}_{-400}	90^{50}_{-90}	18.24
Koronis	2360^{+2240}_{-2090}	70^{+60}_{-70}	12.59
Themis	1500^{+2650}_{-1010}	70^{+75}_{-70}	15.41
Meliboea	640 ± 10	15^{+10}_{-5}	7.02
Ursula	1060^{+3540}_{1060}	45 ± 45	4.30
Alauda	640 ± 50	95^{+15}_{-20}	27.77

Table 3. Estimated maximum ages from this work, Brož et al. (2013), and Spoto et al. (2015).

Name	Current estimates (Gyr)	Brož et al. (2013) (Gyr)	Spoto et al. (2015) (Gyr)
Eunomia	2.67	3.00	2.35
Maria		4.00	2.35
Koronis	4.60	3.50	2.24
Themis	4.15	3.50	<4.60
Meliboea	0.65	<3.00	
Ursula	4.60	<3.50	4.52
Alauda	0.69	<3.50	

For the case of the Alauda family, we had 32 C intervals with more than 10 asteroids, and 30 degrees of freedom. The Alauda family should be 640 ± 50 Myr old, with $V_{\mathrm{EJ}} = 95^{+15}_{-20}$ m s^{-1}, and a secondary minimum at lower values of V_{EJ}. Our results for the six families are summarized in Table 2, where we display the name of the family, the estimated age, the values of V_{EJ}, and the limit used for $\psi_{\Delta C}$.

Overall, we found that no family is nominally older than 2.7 Gyr, but uncertainties are too large for the Koronis, Themis, and Ursula families for a positive conclusion to be reached. We compared our results with the maximum age estimates from Brož et al. (2013) and from the more recent work of Spoto, Milani & Knežević (2015), that found estimates for the family ages with a V-shape method in the $(a, 1/D)$ domain. Table 3 shows the maximum estimated ages

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[1] We should caution the reader that other methods to estimate the uncertainties for the estimated parameters are also used in the literature. For instance, one can compute the 1σ, 2σ, or 3σ χ^2 values and sum these to the minimum observed value of χ^2 to obtain estimates of the errors at 1σ, 2σ, or 3σ levels (Press et al. 2001). Since age estimates for very old families, such as those studied in this work, tend to produce shallow minima, here we prefer to use the Vokrouhlický et al. (2006a,b,c) approach, so as to provide a more limited range of estimated values. But larger values of the error estimates are possible.

Table 4. Estimated age, ejection velocity parameter, and maximum possible age for six 'Brož' families, when $K = 0.1$ W m^{-1} K^{-1}.

Name	Age (Myr)	V_{EJ} (m s^{-1})	Max. Age (Gyr)
Eunomia	>4600	80 ± 40	>4.6
Koronis	4500^{+100}_{-300}	5^{+125}_{-5}	4.6
Themis	2240^{+2360}_{-1420}	60^{+80}_{-60}	4.6
Meliboea	1250 ± 50	10^{+20}_{-10}	1.3
Ursula	3150^{+1450}_{-3150}	15^{+80}_{-15}	4.6
Alauda	1020^{+80}_{-40}	95^{+20}_{-10}	1.1

from this work (mean values plus errors), from Brož et al. (2013) and from Spoto et al. (2015).[2]

To within the uncertainties, our estimates tend to be in agreement with previous results, with the two possible exceptions of the Alauda and Meliboea families, that could potentially be younger than previously thought (but uncertainties for these two families may be larger if different approaches for the error on the χ^2-like variable were used). Masiero et al. (2012) investigated the effect that changes in the nominal values of the parameters affecting the Yarkovsky and YORP forces may have on the estimate of the age of the Baptistina family and found that the parameters whose values most affected the strength of the Yarkovsky force were the asteroid density and the thermal conductivity. Since the largest variations were observed for changes in the values of the family thermal conductivity, for the sake of brevity in this work we concentrate our analysis on this parameter. Maximal ages can be found if one consider a value of the thermal conductivity of $K = 0.1$ W m^{-1} K^{-1}. We repeated our analysis for the six 'Brož' families, and this larger value of K, and our results are summarized in Table 4, where we display the estimated ages, ejection velocity parameter, and maximum possible age.

The ages of the S-type families Koronis and Eunomia in these simulations were larger than 4.5 Gyr, but that it is just an artefact caused by the improbably high value of K (0.1 W m^{-1} K^{-1}) used for these simulations (typical values of K for S-type families are of the order of 0.001 W m^{-1} K^{-1}). More interesting were the results for the C-complex groups: while the maximum possible ages for the Themis and Ursula families were beyond 3.0 Gyr, none of the groups, even in this very favourable scenario, has nominal ages old enough to reach the earliest estimates for the LHB (3.8 Gyr ago). The implications of this analysis will be further explored in the next section.

4 DYNAMICAL EVOLUTION OF OLD FAMILIES

To study the possible survival of any of the largest members of the oldest main belt family over $\simeq$4 Gyr, we performed simulations with the *SYSYCE* integrator (Swift+Yarkovsky+Stochastic YORP+Close encounters) of Carruba et al. (2015), modified to also account for past changes in the values of the solar luminosity. The numerical set-up of our simulations was similar to what discussed in Carruba et al. (2015): we used the optimal values of the Yarkovsky parameters discussed in Brož et al. (2013) for C- and S-type asteroids, the initial spin obliquity was random, and normal reorientation time-scales due to possible collisions as described in Brož (1999) were considered for all runs. We integrated our test particles under the influence of all planets, and obtained synthetic proper elements with the approach described in Carruba (2010b).

We generated fictitious families with the ejection parameter V_{EJ} found in Section 3 (for the Maria family we used the same value found for the Eunomia group, i.e. $V_{\mathrm{EJ}} = 90\,\mathrm{m\,s^{-1}}$), and integrated these groups over 4.0 Gyr. Also, since only bodies larger than 4 Km in diameter were shown to survive in the Cybele region over 4.0 Gyr, following the approach of Carruba et al. (2015) we generated families with size–frequency distributions (SFD) with an exponent $-\alpha$ that best-fitted the cumulative distribution equal to 3.6, a fairly typical value, and with diameters in the range from 2.0 to 12.0 km. The number of simulated objects was equal to the currently observed number of family members with diameters between 2.0 and 12.0 km.

For each of the simulated families, we computed the fraction of objects that remained in a box defined by the maximum and minimum value of $(a, e, \sin(i))$ associated with current members of the seven families as a function of time, the fraction of objects with $4 < D < 6$ km, and the time evolution of the $-\alpha$ exponent. These parameters will help estimating the dynamical evolution of the simulated families: the lower the values of these numbers, the more evolved and diffused should be the family. Also, to quantify the dispersion of the family members as a function of time, we also computed the nominal distance velocity cutoff d_0 for which two nearby asteroids are considered to be related using the approach of Beaugé & Roig (2001), that defines this quantity as the average minimum distance between all possible asteroid pairs, as a function of time (typical values are of the order of 50 m s^{-1}, significantly larger values would indicate that the family was dynamically dispersed beyond recognition).

Our results for the Koronis family are shown in Fig. 4, where we display in panel A the time evolution of the fraction of all asteroids remaining in the Koronis family region (blue line) and of the objects with $4 < D < 6$ km (green line). Panel B shows the time evolution of the $-\alpha$ exponent, while panel C displays d_0 as a function of time. The Koronis family is in a dynamically less active region, so a larger fraction of its original population survive the simulation, but this is not the case for all investigated families. Our results at $t = 3.8$ Gyr, the minimum estimated age for the end of the LHB, are reported in Table 5.

Overall, the Meliboea and Alauda synthetic families were dispersed beyond recognition. All families had values of $-\alpha$ at $t = 3.8$ Gyr much shallower than the initial value (3.6), and compatible with typical values of background asteroids ($\simeq$2). This does not necessarily mean that all paleo-families should be characterized by a shallow SFD. The initial SFD could have been much steeper, and collisionary evolution could have replenished the population of asteroids at smaller sizes. There are indeed some indications that some potential paleo-families, such as Itha, could be characterized by a relatively steep SFD (Brož, Cibulkova & Rehak 2012). However, dynamical effects alone indeed tend to remove smaller size bodies and to produce families with shallower SFD. In regimes where dynamical effects are predominant and the initial SFD was not too steep, we would expect paleo-families to be characterized by a shallow SFD. Also, according to the values of d_0 found in

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[2] In Spoto et al. (2015), the authors found estimates for the left and right semimajor axis distributions of family members with respect to the family barycentre. Results in Table 3 are for the maximum possible estimates, among the two, when available (for the Maria and Ursula there was data for just one of the family wings, there was no estimate available for the Meliboea and Alauda families. The Eunomia parent body may have experienced two or more impacts, according to these authors. Table 3 reports the estimated age of the oldest impact).

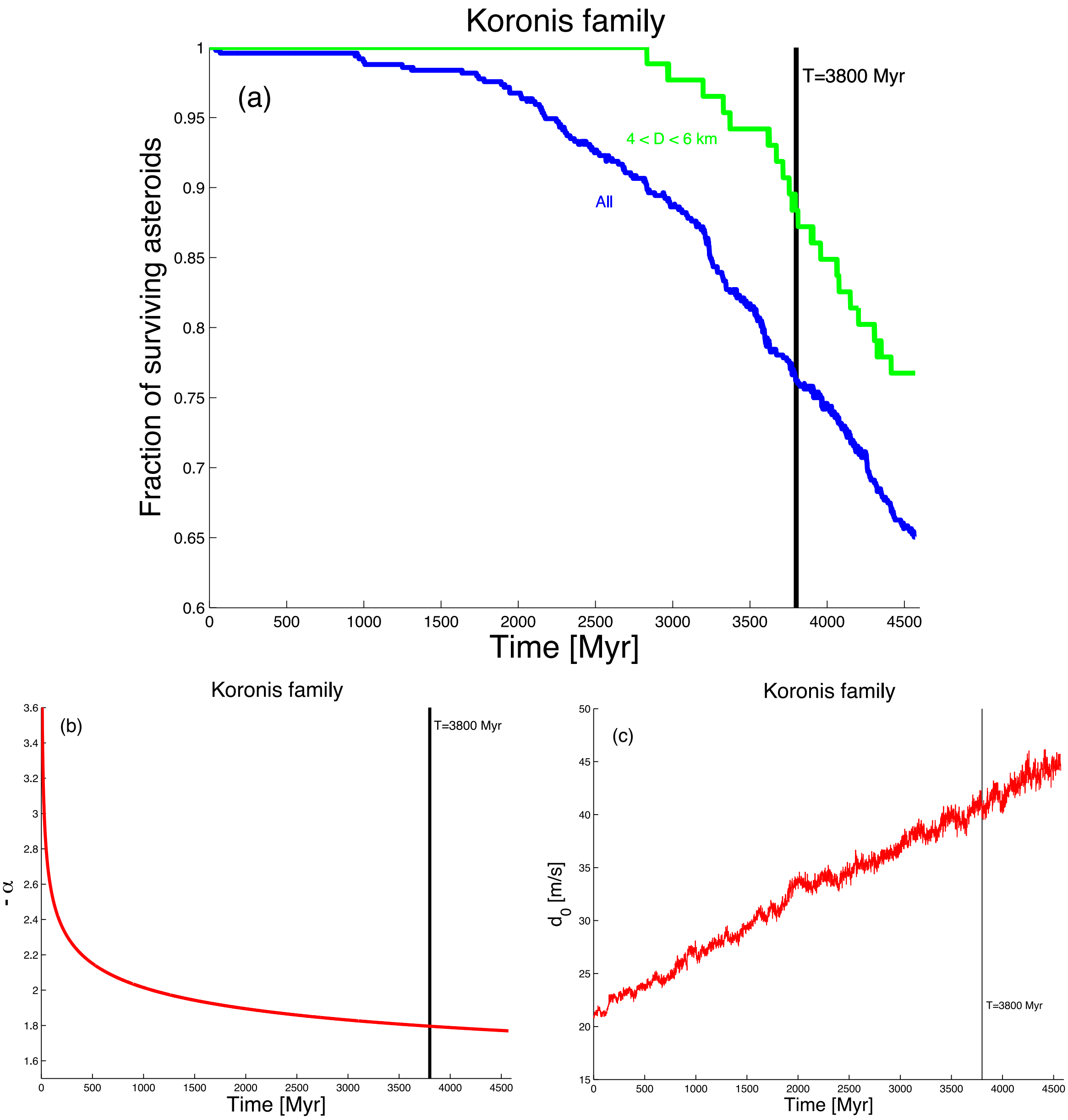

Figure 4. Panel A: the fraction of particles of all sizes (blue line) and with $4 < D < 6$ km (green line) that remained in the Koronis orbital region as a function of time. Panel B: the time evolution of the $-\alpha$ exponent of the size cumulative distribution. Panel C: time evolution of d_0, the nominal distance velocity cutoff necessary to recognize two objects as members of the dynamical family.

Table 5. Value at $t = 3.8$ Gyr of the fraction of particles with all diameters surviving the simulation (second column), of those with $4 < D < 6$ km (third column), of the $-\alpha$ exponent (fourth column), and of d_0 (fifth column).

Name	Fraction of surviving asteroids (all sizes) (per cent)	Fraction of surviving asteroids ($4 < D < 6$ km) (per cent)	$-\alpha$	d_0 (m s^{-1})
Eunomia	36.8	53.3	1.7	77.3
Maria	72.7	92.0	1.7	63.5
Koronis	76.2	88.3	1.8	42.2
Themis	69.5	89.4	2.0	92.3
Meliboea	9.0	16.6	2.4	375.2
Ursula	65.1	92.1	2.0	137.4
Alauda	22.1	8.5	1.9	171.4

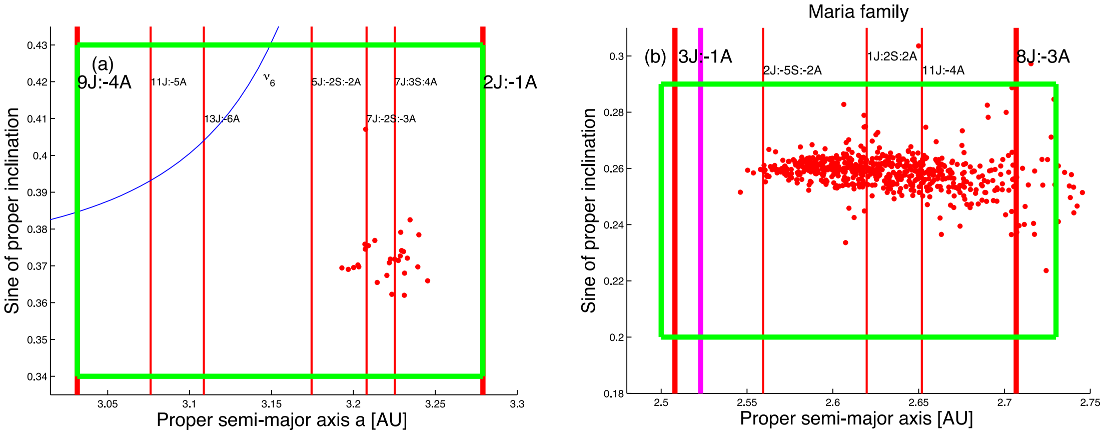

Figure 5. Projection at $t = 3.8$ Gyr in the (a, sin (i)) plane of members (red full dots) of the simulated Alauda (panel A) and Maria (panel B) families. Vertical red lines display the location of the main local mean-motion resonances, the magenta vertical line in panel A refers to the approximate location of the chaotic layer near the boundary of the 3J:-1A mean-motion resonance, where particle are unstable on time-scales of 100 Myr. The blue line in panel B show the approximate location of the ν_6 secular resonance. Green lines define the boundary in the (a, sin (i)) plane of the orbital region of the two families.

this work, only the synthetic Koronis, Maria, and possibly Eunomia family would be recognizable, with some difficulties, with respect to the background (typical values of d_0 depends on the local density of asteroids, but are usually of the order of 50–60 m s^{-1}). To help visualize the difference between a completely dispersed family, such as Alauda, and a relatively well preserved one, such as Maria, we show in Fig. 5 a projection in the (a, sin (i)) of the outcome of our simulations at $t = 3.8$ Gyr. While only a handful of the largest members of Alauda survived up to this time, the simulated Maria family, while dispersed, could still be recognizable in this domain.

Can any paleo-family still be observable today? As we discussed, paleo-families would be difficult to recognize with traditional methods such as HCM, being characterized by a shallow SFD, a significant depletion in small family members (those less than 5 km in diameter), and a large spread among the surviving members. Paleo-families belonging to fairly typical taxonomical classes, such as C- and S-type, would be extremely hard to recognize. It was however proposed that V-type asteroids in the Eunomia orbital region could have been fragments of a paleo-Eunomia family associated with the disruption of Eunomia parent body crust (Carruba, Michtchenko & Lazzaro 2007; Carruba et al. 2014b). We checked the $-\alpha$ value of the 16 V-type photometric candidates SFD currently in the Eunomia orbital region (defined according to our box criteria), and we found a value of 1.95. While this result should be considered with caution, given the limited number of V-type asteroids in the region and possible limitations caused by observational incompleteness, the very shallow SFD of these objects suggests, in our opinion, that an origin from a paleo-Eunomia family is not incompatible with the results of this work.

5 CONCLUSIONS

In this work, we performed the following.

(i) Identified members of the seven old 'Brož' families in a new domain of proper elements, *gri* slope and $z' - i'$ colours. Once taxonomical and dynamical interlopers were removed, preliminary estimates of the maximum possible family ages were obtained.

(ii) Used a 'Yarko-YORP' Monte Carlo approach (Carruba et al. 2015) that includes the effects of the stochastic YORP effect of Bottke et al. (2015) and past changes in values of the solar luminosity to obtain refined estimates of the family ages, when possible. Our nominal age estimates are lower than results of other groups that did not consider the stochastic YORP effect, as expected, but compatible to within the uncertainties. Even allowing for the maximum possible value in the thermal conductivity of the simulated families, no CX-complex group could have a nominal age dating from the latest phases of the LHB.

(iii) Simulated with the *SYSYCE* symplectic integrators (Carruba et al. 2015) that accounts for the Yarkovsky and stochastic YORP effects, and past changes in solar luminosity, the dynamical evolution of members of fictitious original seven 'Brož' families. Under the assumptions of our model (no collisional evolution, and an initial SFD with a $-\alpha$ exponent for the population of objects with $2 < D < 12$ km equal to 3.6), any 'paleo-family' that formed between 2.7 and 3.8 Gyr ago would be characterized by a very shallow SFD, a depletion in smallest ($D < 5$ km) members, and a significant spread among the surviving fragments. Only families in dynamically less active regions, such as the Koronis family in the pristine zone of the main belt, could have potentially partially survived 3.8 Gyr of dynamical evolution and not be completely dynamically eroded. The V-type asteroids in the Eunomia orbital region are characterized by a very shallow SFD, and could potentially be compatible with a paleo-Eunomia family, as suggested in the past (Carruba et al. 2007, 2014b).

Overall, the main result of this work is that some paleo-families, particularly the initially most numerous ones, or those in dynamically less active parts of the main belt, could still be visible today, but would be of rather difficult identification, especially for the case of families belonging to fairly typical taxonomical types, such as the C- and S-types. Other effects not considered in this work, such as collisional cascading or comminution (Brož et al. 2013), close encounters with massive asteroids (Carruba et al. 2003), secular dynamics involving massive asteroids (Novaković et al. 2015) could all have contributed to further disperse paleo-family members, perhaps beyond recognition. Yet the quest for the identification of a paleo-family remain, in our opinion, a very worthy subject of research in asteroid dynamics. If such family could be found, such as is possibly the case for the V-type asteroids in the Eunomia orbital region, it could provide precious clues about a very early stage of our Solar system. Finding and identifying paleo-families remains therefore a very value line of research in asteroid dynamics.

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