Planetary and Space Science 166 (2019) 90–100

Contents lists available at ScienceDirect

Planetary and Space Science

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

On the age of the Beagle secondary asteroid family

V. Carruba

São Paulo State University (UNESP), School of Natural Sciences and Engineering, Guaratinguetá, SP, 12516-410, Brazil

ARTICLE INFO

Keywords:
Minor planets
Asteroids: general
Minor planets
Asteroids: individual: (656) Beagle
Celestial mechanics

ABSTRACT

The Beagle family is a C-type subgroup of the Themis family, in the outer main belt. Previous works suggested that it could be younger than 20 Myr and a possible source for the dust in the $i \simeq 1.4^\circ$ α zodiacal dust band. Here we took advantage of a much larger database for Beagle family members to revisit previous age estimates of this group. Standard dating techniques based on the family V-shape or on Monte Carlo methods of Yarkovsky and YORP mobility suggest that i) there might be a dichotomy for the inner and outer part of the Beagle family, which may be either two separate families or the product of an anisotropic ejection velocity field and that ii) the age of the possibly younger outer part of the Beagle family should be 35^{+65}_{-35} Myr. The past convergence of Beagle longitude of the node is compatible with a family age of $\simeq 14$ Myr, when (1678) Glarona is used as a reference orbit. Without further information on Beagle members spin states, however, only very lower limits on the family age can be currently obtained when the Yarkovksy force is accounted for.

1. Introduction

Little altered recently born families may provide direct information about the physics of break-up events. Families younger than $\simeq 20$ Myr may be precisely dated using the method of backward convergence of the longitudes of node Ω and pericenter ϖ with respect to the presumed parent body (Nesvorný et al., 2002; Nesvorný and Bottke, 2004), or backward integration method (BIM). This method allows for dating asteroid families with a precision not available for other, more evolved groups, as well as for obtaining information on the average drift rates induced over the estimated family age by the Yarkovsky and, in some cases, YORP forces. Several asteroid groups have been recently dated using this approach, like the Karin cluster (Nesvorný et al., 2002; Nesvorný and Bottke, 2004), the Veritas family (Nesvorný and Bottke, 2004; Carruba et al., 2017), the Nele family (Carruba et al., 2018), the Lorre family (Novaković et al., 2012b), and the Beagle family (Nesvorný, 2008), among others. Among these groups, only the Lorre and Beagle families are C-type collisional families located in relatively stable dynamical regions.[1] The Veritas family is a C-type family, but is located near the 2J: 1A mean-motion resonance with Jupiter, and it is crossed by the diffusive 5J: 2S: 2A three body resonances with Jupiter and Saturn, and other three-body resonances, which only allows us to apply the BIM to a limited subset of regular family members, not on chaotic orbits. The Karin and Nele families are S-type families, and S-type asteroids are thought to have undergone some thermal evolution since the time of their formation. This only leaves the Lorre and Beagle families as C-type families in dynamically stable regions. The Lorre family is a 19 asteroids cluster, with most of its members made by multi-opposition or single-opposition objects, located in the central highly inclined main belt, first identified by Novaković et al. (2011). Novaković et al. (2012b) estimate this family age to be 1.9 ± 0.3 Myr, making it one of the youngest known families in the main belt.

The Beagle family, the subject of this research, is a sub-family of the larger Themis group. It was first identified by Nesvorný (2008), it is a possible source of the $i \simeq 1.4^\circ$ α zodiacal dust band (Sykes; Nesvorný, 2008), and it should be less than 20 Myr old (Nesvorný, 2008). It is classified as a C-type group with Family Identification Number (FIN) 620 in (Nesvorný et al., 2015). The active asteroid (7968) Elst-Pizzaro (Elst et al., 1996; Hsieh and Jewitt, 2006) is a member of this group, and it has been suggested that some members of this class of asteroids, experiencing comet-like activity, could indeed be explained as members of young C-type families (Nesvorný, 2008).

E-mail address: valerio.carruba@unesp.br.

[1] Other C-type groups were actually recently identified, among them we mention the family around P/2012 F5 (Gibbs) (Novaković et al., 2014), the Mandragora cluster (Pravec et al., 2018), and the very interesting case of a family associated with a binary main belt comet, 288P (Novaković et al., 2012a; Hsieh et al., 2018) that could also be another secondary family of the Themis family. Some of these groups are, however, very compact in proper element domains and may be the result of a fission event (Jacobson and Scheeres, 2011) or the effect of a cratering event onto a nearly critically rotating primary (Vokrouhlický et al., 2017), rather than traditional asteroid families formed by collision, as most likely Beagle and Lorre are.

https://doi.org/10.1016/j.pss.2018.08.004
Received 6 March 2018; Received in revised form 6 June 2018; Accepted 29 August 2018
Available online 6 September 2018

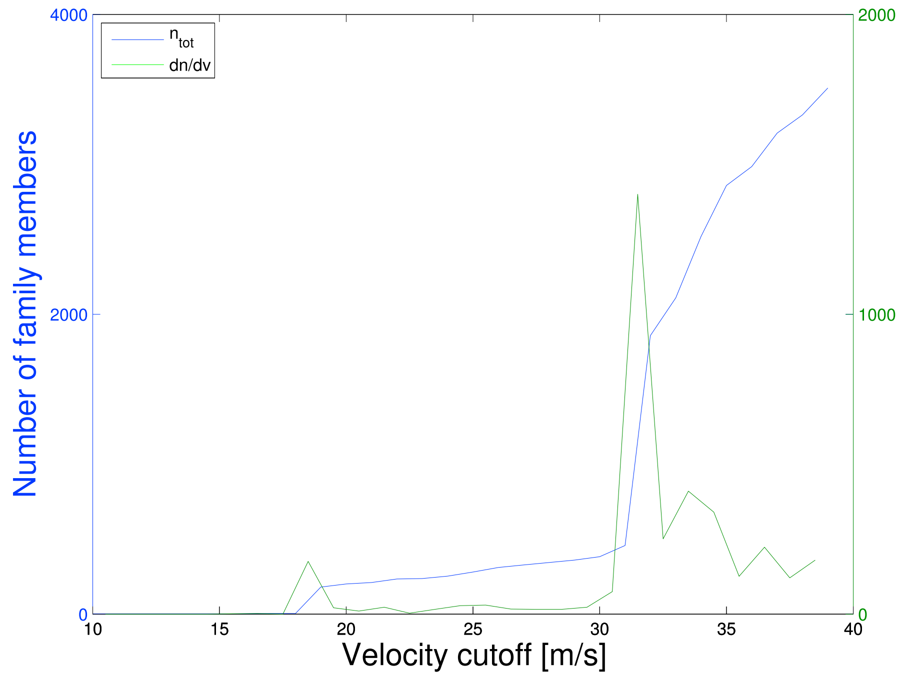

Fig. 1. Number of Beagle family members (blue line) and change in the number of family members (green line) as a function of the velocity cutoff. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

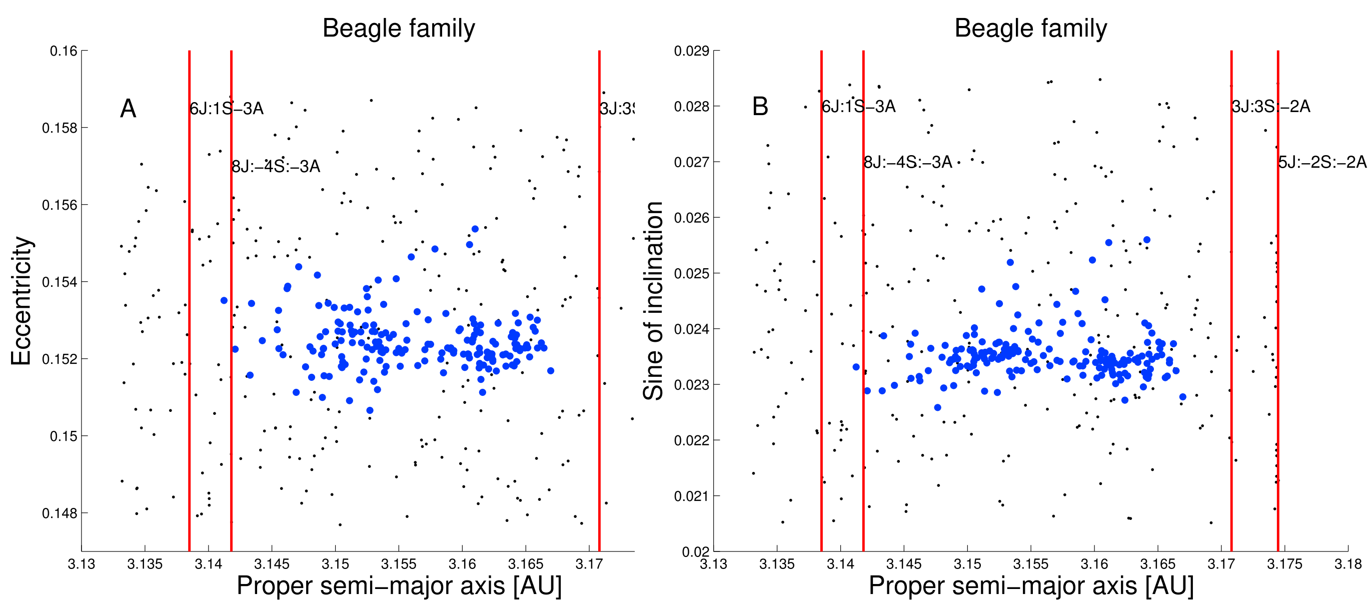

Fig. 2. An (a, e) (panel A) and $(a, \sin i)$ (panel B) projection of asteroids in the local background of the Beagle family. Vertical lines display the location of the main mean-motion resonances in the region. Blue full dots show the orbital location of members of the Beagle family, while black dots display the location of asteroids in Beagle local background. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Since the Beagle family has more than doubled in size since the time of its identification, and since new techniques improving the precision of family dating with BIM have been recently introduced, we believe that a new study of this very interesting group should be warranted.

In this work, we will first try to address one of the main problem with the Beagle family: being a subgroup of the Themis family, we first have to be able to distinguish among members of the Beagle family and members of the larger parent family. Once a reliable Beagle family membership has been established, we then applied standard dating techniques for obtaining estimates of the age and initial ejection velocity field of the Beagle family. Then, we applied BIM to understand if the current Beagle family is younger, or not, than 20 Myr. In the last section of this paper we present our conclusions.

2. Family identification and dynamical properties

Since the Beagle family is a sub-family of the larger Themis group, one of the first problem dealing with this sub-family is how to reliably

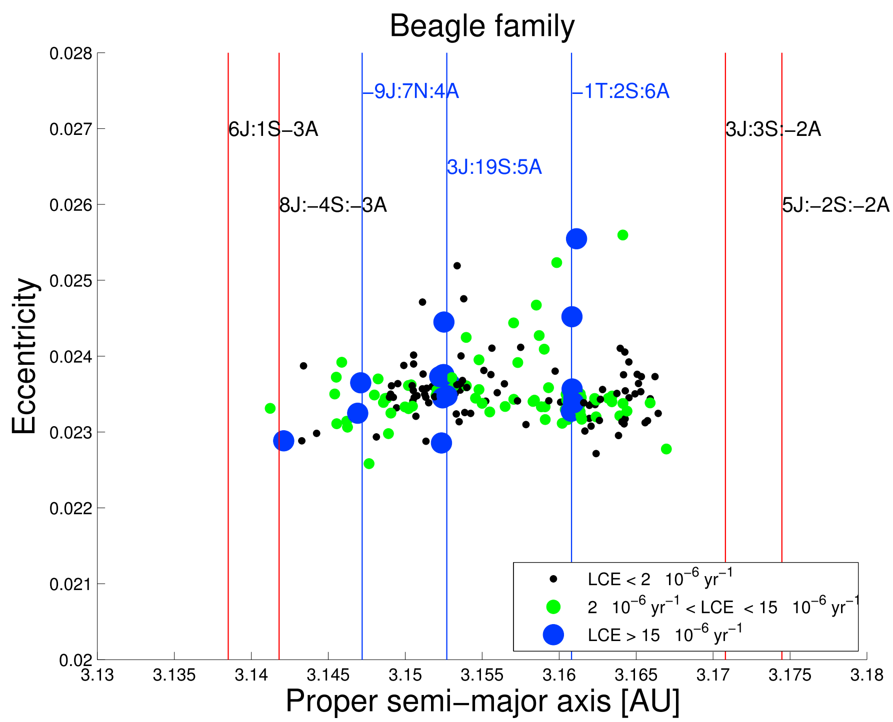

Fig. 3. A $(a, \sin i)$ projection of Beagle family asteroids. Objects with Lyapunov times T_L longer than 5×10^5 yr are shown as black dots. Objects with $6.7 \times 10^4 < T_L < 5 \times 10^5$ yr are displayed as green full circles, while objects with $T_L < 6.7 \times 10^4$ yr are shown as blue full circles. Vertical lines display the orbital location of local mean-motion resonances. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

distinguish members of the Beagle family from Themis asteroids (Novaković et al., 2012b). As a first step in our analysis, we used the Beagle family as identified in Nesvorný et al. (2015) using the Hierarchical Clustering Method (HCM (Bendjoya et al., 2002),) and a cutoff of 25 m/s. 148 members of this dynamical group were identified in that work, which is 2.3 times more numerous than the 65 members group studied in Nesvorný et al. (Nesvorný, 2008).[2]

Several new asteroids have been discovered in the region since 2015, some of which could be potential members of the Beagle family. To identify some of these, we first downloaded the catalog of synthetic proper elements from the AstDyS site (http://hamilton.dm.unipi.it/astdys, Knežević & Milani (Knežević and Milani, 2003)), accessed on December 11th, 2017), and then applied the HCM to asteroids in the region, using (656) Beagle as first object in the chain. The method has been described in several papers (see for instance Zappala et al. (1990), Bendjoya & Zappalà (Bendjoya et al., 2002)). Essentially, given a reference object it will look for asteroids whose distance in proper element domain, defined by a metric:

$$d = na_C \sqrt{\frac{5}{4}\left(\frac{\Delta a}{a_C}\right)^2 + 2(\Delta e)^2 + 2(\Delta \sin i)^2}, \tag{1}$$

where na_C is the heliocentric velocity of an asteroid on a circular orbit having semi-major axis a_C, and $\Delta a = a_i - a_C$, $\Delta e = e_i - e_C$, and $\Delta \sin i = \sin i_i - \sin i_C$ denote the difference in proper elements between a given i-th asteroid and the reference body. If an asteroid is to within the cutoff distance d from the reference body, it will be added to the family list, and the procedure will be repeated for this object as a reference, until no new family member is encountered. The distances d are usually measured in m/s.

[2] We could not find the Beagle family in the catalog of families from Milani et al. (2014).

Fig. 1 displays the number of Beagle family members as a function of the velocity cutoff d, as well as the change in number for each 1 m/s increase in cutoff. For $d = 20$ m/s the Beagle family starts connecting to well-known large members of the Themis family, such as (171) Ophelia and (383) Janina, so we decided to be conservative and to work with the family obtained at a cutoff of $d = 19$ m/s. The Beagle family completely merges with the Themis family at a cutoff of $d = 32$ m/s. If we define the local background of the Beagle family using the criteria of (Carruba & Nesvorný, 2016), the range of values for the Beagle family at $d = 19$ m/s in proper $a, e, \sin i$ is 3.1331–3.1745 au, 0.1476 to 0.1589, and 0.0205 to 0.0285, respectively. There are 180 objects in this group (and 343 in the local background so defined), 32 of which were not listed in the Nesvorný et al. (2015) family. Fig. 2, panel A and B, displays (a, e) and $(a, \sin i)$ projections of members of the Beagle family, shown as full blue circles. Asteroids in the background are shown as black dots. Vertical lines display the location of local three-body resonances, as listed in Nesvorný et al. (Nesvorný and Morbidelli, 1998).

Not all the members of the Beagle dynamical family nor of the asteroids in the local background should necessary be actual members of the family. Later on we will further investigate this issue by using BIM for all these bodies. As discussed by previous authors, the Beagle family is located in a relatively dynamically stable region of the main belt. Only one family member interacts with the 8J: 4S: 3A three-body resonance, and most of the family members and background objects are regular or just mildy chaotic. To better understand the local dynamics, we identified the asteroids with Lyapunov Characteristics Exponents (LCE) larger than 2×10^{-6} yr^{-1}. Data on the LCEs was obtained from AstDyS. Fig. 3 display objects with LCE in three interval range, while the figure caption discuss the equivalent limits in terms of Lyapunov times, that are the inverse of LCEs.

Fig. 3 displays an $(a, \sin i)$ projection of Beagle family asteroids. Apart from the body interacting with 8J: 4S: 3A three-body resonance, there were only nine more mildy chaotic Beagle family members. Three three-

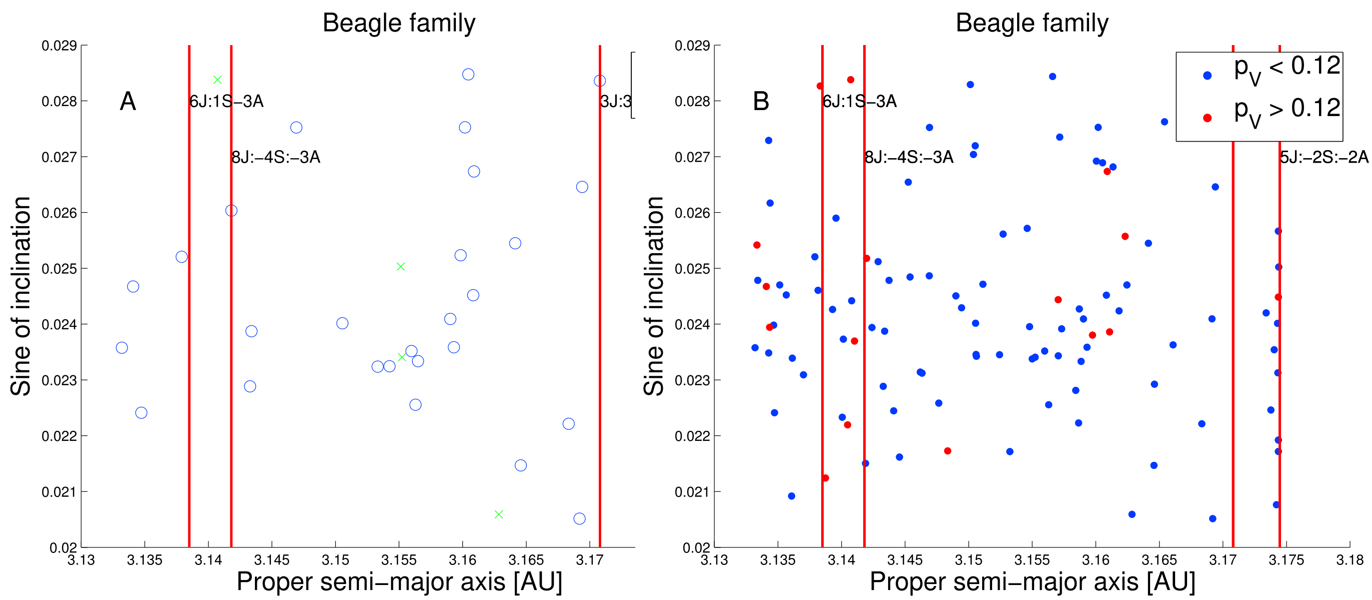

Fig. 4. Panel A: An $(a, \sin i)$ projection of C-type (blue circles) and B-type (green X) asteroids in the local background of the Beagle family. Panel B: objects with WISE geometric albedo $p_V < 0.12$ (blue dots) and $p_V > 0.12$ (red dots). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

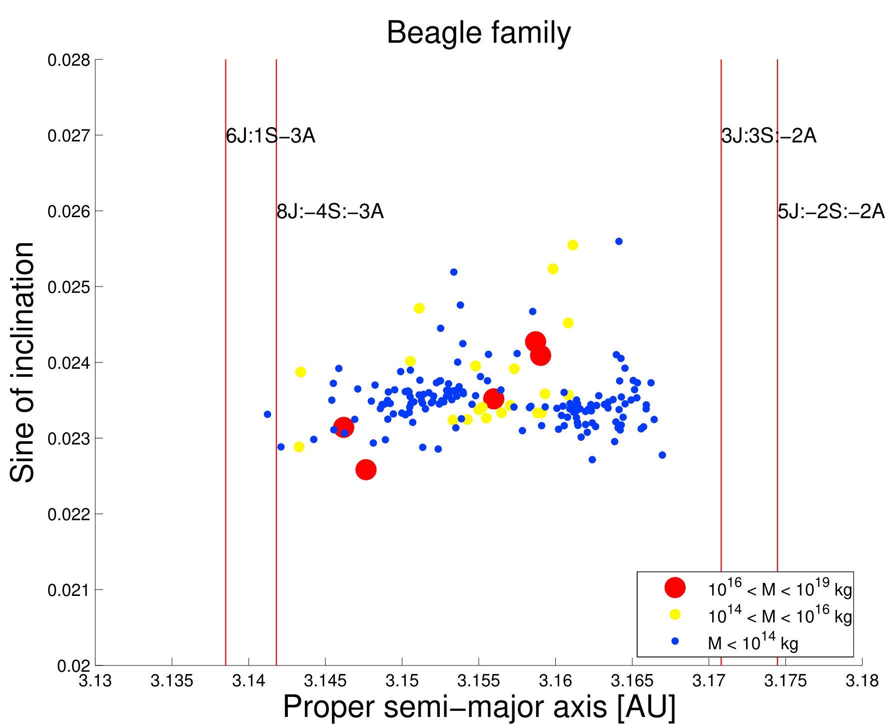

Fig. 5. An $(a, \sin i)$ projection of Beagle family asteroids. The color and size of the symbols reflect the estimated asteroid mass. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

body resonances, as listed in the catalog from Gallardo (2014), could potentially be responsible for this behavior. Their orbital identification and argument are listed in blue in the Fig..[3]

[3] We must warn the reader that the identification of these resonances needs to be confirmed by an analysis of the resonant argument of the asteroids in the chaotic regions. Pending such an analysis, the names and identifications of these resonances remain hypothetical.

Finally, we also checked the importance of local secular resonances. We computed all secular resonances up to order six for the region of Beagle asteroids. Two secular resonances cross the region, the $g - 2g_6 + g_5 + s - s_6 = 2\nu_6 - \nu_5 + \nu_{16}$ and the $g - g_5 + 2s - 2s_6 = \nu_5 + 2\nu_{16}$. No Beagle member is however found to within ± 0.3 arcsec/yr from the resonance center. Secular dynamics should therefore play a minor role for this family. In the next section we will revise the physical properties of local asteroids.

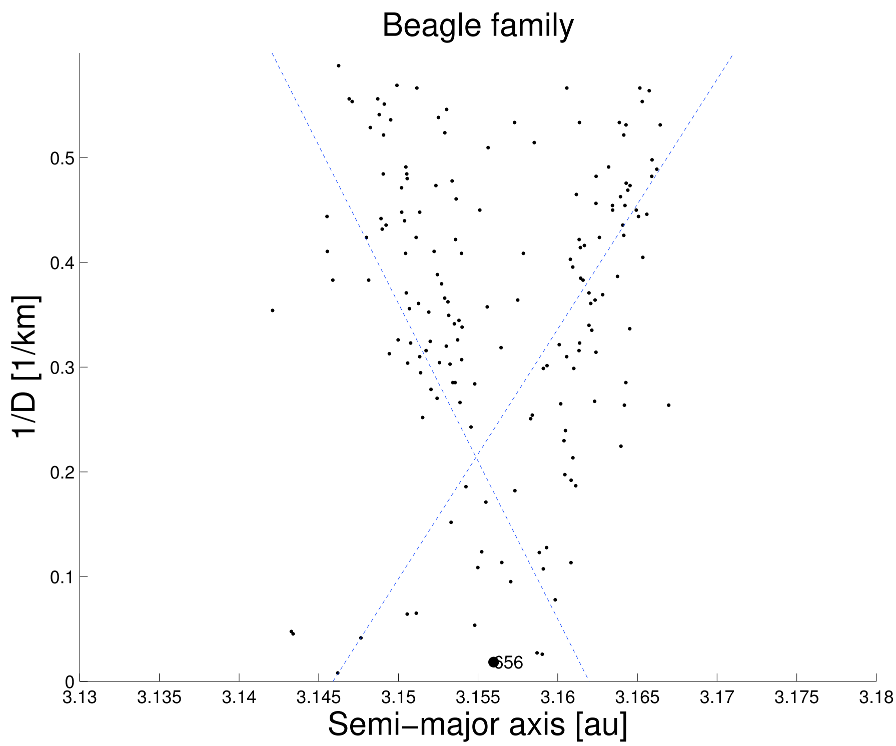

Fig. 6. The V-shape in the $(a, 1/D)$ domain for the Beagle family. The black full dot display the orbital location of (656) Beagle.

3. Physical properties

Nesvorný et al. (2015) list Beagle as a C-type family, with a mean geometric albedo p_V of 0.07. (656) Beagle and (90) Antiope were considered offset with respect to the family center (Nesvorný, 2008), and their family status was listed as doubtful in that paper. Our analysis of the background region of the Beagle family confirms that of Nesvorný et al. (2015). There were 34 asteroids for which taxonomic information was either available or could be derived using the method of DeMeo & Carry (DeMeo and Carry, 2013) from photometric data in the Sloan Digital Sky Survey-Moving Object Catalog data (SDSS-MOC4; Ivezić et al. (Ivezić, 2001)). All of them belong to the C-complex, with 30 C-type and 4 B-type asteroids. 107 asteroids have geometric albedo and absolute magnitude information available in the WISE and NEOWISE, AKARI, or IRAS databases (Masiero et al., 2012; Ishihara et al., 2010; Ryan and Woodward, 2010; Mainzer et al., 2016) that satisfied the good signal-to-noise ratio criteria described in Spoto et al. (2015). 17 of them (15.9% of the total) have $p_V > 0.12$ and could be potential albedo interlopers of either the Beagle or of the Themis family. The median albedo of the 21 Beagle dynamical family asteroids for which this information was available was $p_V = 0.079$. Two asteroids, (3591) Vladimirskij and (3615) Safronov, had albedo higher than 0.12 and were considered interlopers. It should, however, be stated that the WISE albedo of (3591) Vladimirskij is compatible with a C-type classification while its AKARI value is not. Fig. 4, panel A displays an $(a, \sin i)$ projection of the asteroid with taxonomic information in the region, while panel B shows the same, but for asteroids with WISE geometric albedo data. Overall, the region is dominated by C-complex asteroids, with a very limited presence of possible interlopers from other taxonomic classes.

We then estimated the masses of local asteroids assuming objects to be spherical with a bulk density equal to 1500 kg m^{-3} (typical value of C-type objects). For objects with available WISE albedo data, we used the WISE p_V value to estimate their radius from the absolute magnitude (Eq. (1) as in Carruba et al. (2003)). For all other objects, we used $p_V = 0.079$, which is the median value of this family.

Fig. 5 shows our results. Apart from (90) Antiope and (656) Beagle, three objects have estimated masses larger than 10^{16} kg: (1027) Aesculapia, (1687) Glarona, and (2519) Annagerman. If (656) Beagle is the parent body of the family, the other four most massive objects could potentially be interlopers in this cluster. Alternately, one of the other three most massive asteroids in the family could also the actual parent body of the family, with (656) Beagle being an interloper in its namesake family. In the next section we will try to obtain preliminary age estimates of the Beagle family.

4. Preliminary age estimates of the Beagle family

Apart from the estimate of (Nesvorný, 2008), that suggested an age of less than 20 Myr for the Beagle family, there are no other recent age estimates for this group in the literature that we know of. Here, we applied three different methods to obtain age estimates of this family: i) the V-shape fitting method of Spoto et al. (2015), ii) the so-called Yarko-YORP Monte Carlo method of (Vokrouhlický et al., 2006a, 2006b), and iii) a method based on the current clustering of secular angle (Carruba et al., 2018). The fist method is based on the slope of the V-shape of the family in the $(a, 1/D)$ domain, from which an age estimate can be obtained. This method neglects the effects of the dispersion caused by the initial ejection velocity field, so that ages obtained with this method tend to be larger than the actual ones. The second method simulates the dynamical dispersion of several fictitious families replicating the conditions after the family break-up under the influence of the Yarkovsky and YORP effects, and compares the results with those of the currenty observed family members. The effects of the initial ejection velocity field (assumed isotropical) are accounted for, but results depends on parameters describing the Yarkovsky force, such as the thermal conductivity and bulk density, that are sometimes poorly known. Finally, the last method simulates the evolution of an initially compact family to check for the minimum time needed to account for the current dispersion in secular angles of the real family. This method only provides a lower limit on the family age.

To begin, we first used the Spoto et al. (2015) method of V-shape fitting in the domain of semi-major axis and inverse diameters. In this

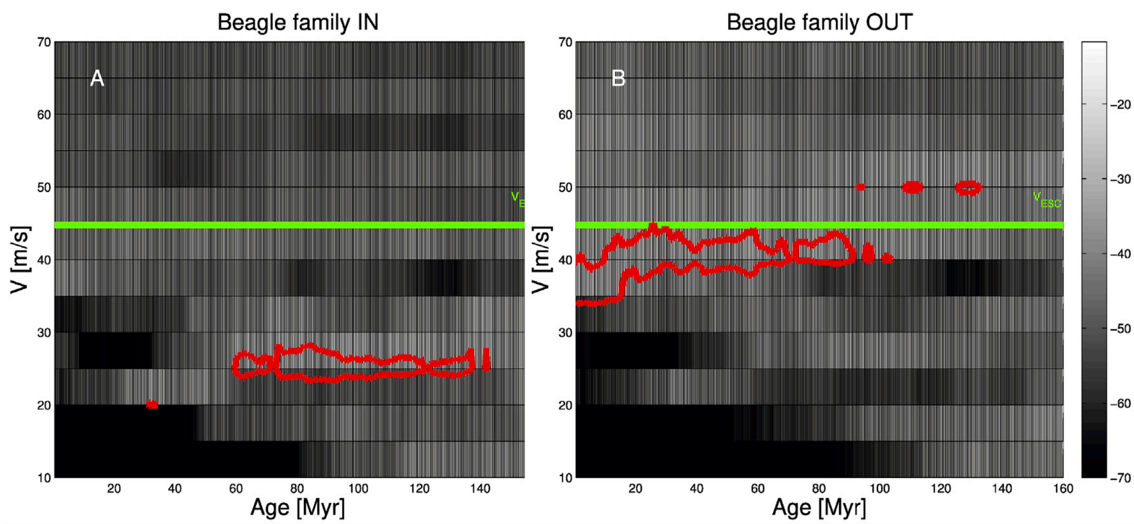

Fig. 7. Target function values for the IN (panel A) and OUT (panel B) parts of the Beagle family. The red line displays the 90.0% confidence level, while the horizontal green line show the estimated escape velocity from the parent body. Values of the V_{EJ} parameter tend to be lower than 1.5 the original escape velocity (Carruba and Nesvorný, 2016). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

method the distribution of asteroids is binned for different values of asteroid inverse diameters, and the asteroids with minimum and maximum semi-major axis values are chosen. The bin sizes are chosen so that the differences in the number of members in two consecutive bins never exceeds one standard deviation. Errors are assigned on the asteroids inverse diameters, and outliers are rejected using an authomatic outlier rejection scheme. The slopes of the two sizes of the family V-shape, the IN and OUT size, in Spoto et al. (2015) notation, are then computed, with their errors. Ages and their errors are then estimated using a Yarkovsky calibration for the values of the da/dt, based on the radar results for the da/dt of asteroid (101955) Bennu.

Fig. 6 displays the V-shape for the solution using (656) Beagle as a reference. We used asteroids with $0.2 < 1/D < 0.55$, so as to avoid including large objects that could be interlopers from Themis and to account for a complete sample, up to the local dynamical limits, according to Spoto et al. (2015) procedure. We found values of the slopes of $S_{IN} = -30.14 \pm 12.31$ for the IN slope and of $S_{OUT} = 23.85 \pm 9.92$ for the OUT slope. If we neglect the effects of the original ejection velocity field, and assume that all asteroids started at the same semi-major axis, then we could obtain upper limits estimates for the age Δt using the relationship (Milani et al., 2014):

$$\Delta t = \frac{1}{S da/dt}, \tag{2}$$

where da/dt is the Yarkovsky drift rate for a 1 km asteroid. Using the values of da/dt from Spoto et al. (2015) for Themis family asteroids, we obtain that the Beagle family should be between 58.4 (IN age) and 75.6 Myr old (OUT age), or 67.0 ± 8.6 Myr old.[4] Alternatively, we can also try to use this data to obtain an estimate of the spread caused by the initial ejection velocity field. Under the assumption that the initial ejection velocity field was symmetric, the initial spread of fragments in the $(a, 1/D)$ domain should have a V-shape, since the transversal component of the ejection velocity field V_T scales inversely with the asteroid diameter (Cellino et al., 1999; Vokrouhlický et al., 2006a). The relationship between the displacement in proper a from the family center a_C, $|a - a_C|$ and the inverse diameter should then be (Vokrouhlický et al., 2006a, 2006b):

$$\left|a - a_C\right| = \frac{2}{n} V_{EJ} \left(\frac{D_0}{D}\right)^{\alpha_{EV}} \cos\theta, \tag{3}$$

where n is the asteroid mean-motion, V_{EJ} is a parameter that describes the width of the fragment ejection velocity distribution (Vokrouhlický et al., 2006a, 2006b), usually of the order of 10–100 m/s, D_0 is equal to 1329 km, and θ is the angle of the fragment velocity relative to the transverse direction of the parent body's orbit. We can assume that at the V-shape edges $\cos\theta = \pm 1$. Data for the Karin and Koronis (Nesvorný et al., 2002; Carruba and Nesvorný, 2016) families suggest that $\alpha_{EV} \simeq 1$. If we assume that the V-shape for the Beagle family in the $(a, 1/D)$ domain observed in Sect. 4 can be mostly caused by the initial ejection velocity field, which may not be the case if the family is evolved, then the value of the ejection parameter V_{EJ} would be related to the absolute values of the IN and OUT slopes by the relationship:

$$V_{EJ} = \frac{n}{2|S|}, \tag{4}$$

Using the values of a_C, S_{IN} and S_{OUT} from this section, then V_{EJ} would be 88.5 and 115.5 m/s, respectively. This would yield a value of 102.0 ± 13.5 m/s, which is significantly higher than the estimated escape velocity from (656) Beagle, that is of the order of 45 m/s. This result suggests that the Beagle family may be older than 10 Myr, so as to account for the observed orbital spreading after the family formation.

To independently verify the age of the Beagle family, we also applied the dating method developed by (Vokrouhlický et al., 2006a, 2006b), modified so as to also account for stochastic YORP (Carruba et al., 2015). In this methods, the semi-major axis distribution of various fictitious families is evolved under the influence of the Yarkovsky, both diurnal and seasonal versions, and YORP effect. The newly obtained distributions of a C-target function computed with the relationship:

$$0.2H = log_{10}(\Delta a/C), \tag{5}$$

where H is the asteroid absolute magnitude, are then compared with the current one using a χ^2 -like variable. More details on the method, such as definitions of the χ^2 -like variable and of the ejection parameter V_{EJ} describing the original spread of the family can be found in the cited papers. Here, to avoid possible contaminations of larger objects from the Themis family, we limit our analysis to objects with $1/D > 0.3$. 132 family members satisfied this selection criteria. Also, since the analysis with Spoto et al. (2015) suggested a possible dichotomy for the inner

[4] The number of Beagle members may, however, be too small to properly apply the V-shape method (see discussion in (Spoto et al., 2015)), which may explain the large uncertainty in the age estimate for the Beagle family.

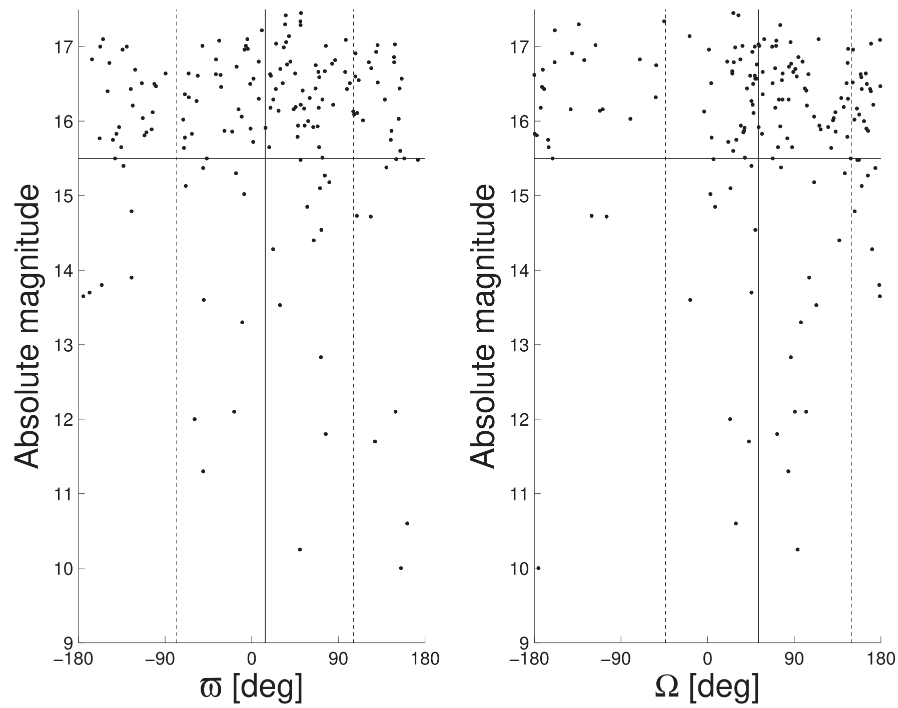

Fig. 8. The current (ϖ, H) and (Ω, H) distributions of members of the Beagle family, where ϖ and Ω are osculating values at the MJD epoch 57200 and H are absolute magnitudes from AstDyS site. The vertical black lines display Ω and ϖ equal to their mean value, while the vertical dashed line show the mean value plus or minus one standard deviation. The horizontal line displays the $H = 15.5$ level, that roughly corresponds to the $1/D = 0.3$ value.

and outer parts of this family, we separated the remaining 132 asteroids into an IN and an OUT group, and determined ages for the two subgroups.

Fig. 7 displays $\Delta\psi_{\Delta C} = \psi_{\Delta C} - \psi_{\Delta Cmin}$ values in the (Age, V_{EJ}) plane for the IN (panel A) and OUT (panel B) parts of the Beagle family. The red lines display the contour level of $\Delta\psi_{\Delta C} = 7.779$, which corresponds to confidence level of 90.0% of the two distribution being compatible (Press et al. (2001), there were 6 intervals in the two C distributions, which, for two estimated parameters, yields 4 degrees of freedom. We assume that the χ^2 -like variable $\Delta\psi_{\Delta C}$ follows a χ^2 cumulative probability distribution, which, for 4 degrees of freedom, at a 90% confidence level corresponds to $\Delta\psi_{\Delta C} = 7.779$. At this confidence level, the IN family should

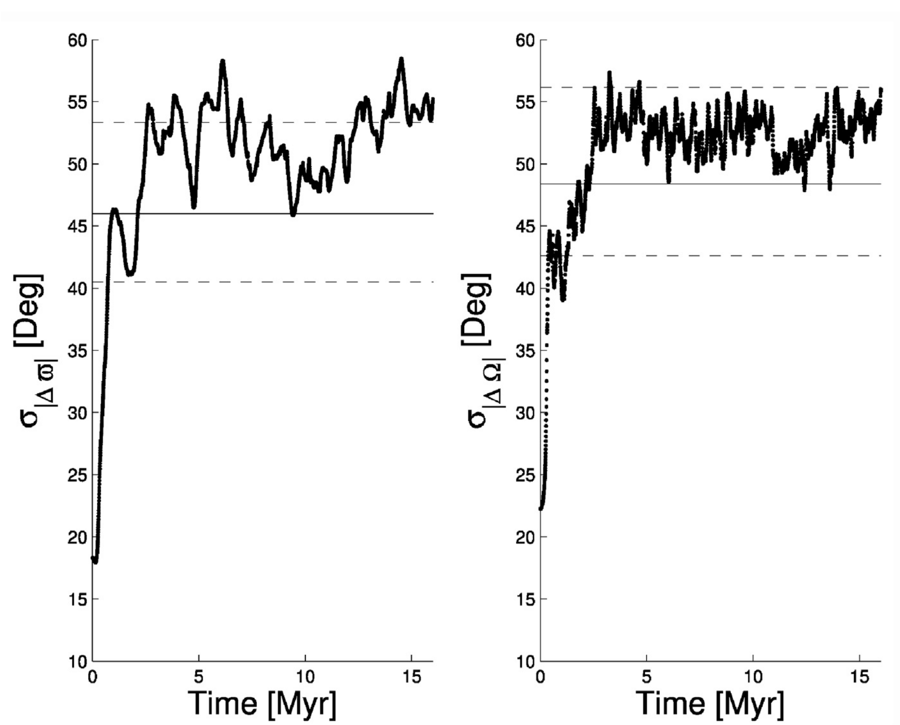

Fig. 9. Time behavior of the standard deviation of the absolute values of differences $\Delta\varpi$ and $\Delta\Omega$ in secular angles with respect to (1687) Glarona. Data from numerical propagation of 107 members of our synthetic realization of the Beagle family started as a compact cluster with 3 m/s ejection field of fragments. The horizontal black line displays the current value of the standard deviation for the real family members, while the horizontal dashed lines show the confidence level for these values (obtained using methods discussed in Sheskin (Sheskin, 2003)).

Table 1
Values of differences in $a, e, \sin i, \varpi$, and Ω for the three family members used as a reference orbit, with respect to the family center. The last two columns displays the minimum time needed to achieve the current values of standard deviations for the three cases, starting from a very compact asteroid family.

Asteroid ID	Δa	Δe	$\Delta \sin i$	$\Delta\varpi$	$\Delta\Omega$	Time $\lvert\Delta\varpi\rvert$	Time $\lvert\Delta\Omega\rvert$
	[au]			[Degrees]	[Degrees]	[Myr]	[Myr]
(656) Beagle	0.000	0.002	0.000	141.0	−228.7	0.3	0.5
(1687) Glarona	0.001	0.001	0.001	36.0	40.6	0.7	1.2
(198672) (2005 BJ42)	0.000	0.001	0.000	−118.1	64.6	1.2	0.4

be 90^{+50}_{-30} Myr old and have a V_{EJ} parameter of 25 ± 3 m/s, while the OUT family should be 35^{+65}_{-35} Myr old and with $V_{EJ} = 40 \pm 6$ m/s. To within the errors, these values are consistent with those obtained with Spoto et al. (2015) method, and, while they are compatible to within the errors with each other, the nominal values are different enough to potentially suggest a possible dichotomy for the ages of the IN and OUT portions of the Beagle family, or the possible existence of an asymmetric ejection velocity field for this family. We will further investigate these hypothesis in the next section of this paper.

Before doing that, however, we first try to set limits on the family age from the current distribution of their members secular angles. For this purpose, we first check what is the current distribution of these angles, and if it shows, or not, sign of being still clustered near particular values. Fig. 8 displays the current distributions of (ϖ, H) and (Ω, H) for Beagle family members. The mean values of ϖ and Ω were of 14.1° and 52.9° respectively, with similar values of standard deviations (96.8° and 92.0°). Neither the ϖ nor the Ω of (656) Beagle itself were within the median value plus or minus one standard deviation. The largest family member to satisfy this criteria is (1687) Glarona, which could potentially be an alternative choice for the family parent body.

As recently performed for the case of the Nele family (Carruba et al., 2018), we conducted the following simple numerical experiment to determine the rate at which the secular angles diverge. At the current epoch, MJD 57200, we constructed a synthetic cluster of 133 objects around the orbit of (656) Beagle. We used a very conservative velocity ejection speed of 3 m/s for each of the fragments and assumed they were launched isotropically in space. This renders an initial spread in both longitude of node Ω and pericenter ϖ of only a fraction of a degree. We intentionally keep the initial velocity small in order not to push the age constraint for the cluster too low. We numerically integrated the orbits of these objects and computed the filtered values of their difference in ϖ and Ω with respect to i) (656) Beagle, ii) (1678) Glarona, and iii) (198672) (2005 BJ42), the family member currently closest in proper elements $a, e, \sin i$ to the position of the Beagle family barycenter. The simulations only included the gravitational effects of the planets, but we neglected the effects of thermal accelerations at this stage of our investigation.

The time behavior of the of the standard deviation of the absolute values of differences $\Delta\varpi$ and $\Delta\Omega$ in secular angles with respect to (1687) Glarona is shown in Fig. 9. Results for the other two reference orbits are displayed in Table 1. Interested readers can found more details on the details of this procedure in Carruba et al. (2018). Current values of the standard deviations are reached on timescales of 1 Myr or less. This is because rates of changes in proper frequencies, $\frac{dg}{da}$ and $\frac{ds}{da}$, are very high in the region of the Beagle family. For members of the Beagle family we found that $\frac{dg}{da} = 1033.3$ arcses/yr and $\frac{ds}{da} = -154.5$ arcsec/yr. These larger rate values explain why convergence in secular angles is lost much faster for the Beagle family than for other families previously studied with BIM, such as the Nele group Carruba et al. (2018). Among the three studied case, the longest minimum needed to achieve the current values of $\Delta\Omega$ was obtained for the case of (1687) Glarona as a reference orbit, which is another hint that this body may be a better candidate of being the parent body of this family than (656) Beagle itself. Further study on this subject will be performed in the next sections of this paper.

5. Past convergence of the longitudes

Following the approach described in [Nesvorný et al. (2003), Nesvorný & Bottke (Nesvorný and Bottke, 2004), Carruba et al. (Carruba et al., 2016; Carruba et al., 2017)] for the Karin and Veritas families, we checked for the past convergence of orbits of members of the Beagle family. Based on our analysis of the previous section, we divided the Beagle family into three subgroups: i) the population of objects with $1/D < 0.3$, possibly quite polluted by interlopers from the Themis family, ii) the IN population with $1/D > 0.3$, and iii) the possibly younger OUT population with $1/D > 0.3$. We integrated these three groups with *SWIFT_MVSF*, which is a symplectic integrator programmed by Levison & Duncan (Levison and Duncan, 1994), under the influence of all planets. This integrator was modified by Brož (Brož) to include online filtering of the osculating elements. The selected orbits were integrated backward in time, with a time step of 1 day, which is less than 1/20 of the period of the fastest perturber (Mercury, with a period of 88 days). The Yarkovsky effect was not included in this integration.

We first checked for the past convergence of ϖ and Ω with respect to (656) Beagle for the members of the Beagle dynamical family. As for the case of the Carruba et al. (Carruba et al., 2017), the Beagle family proximity to the 2J: 1A mean-motion resonance with Jupiter causes a fast precession in the longitudes of pericenters, and precludes the use of the convergence of $\Delta\varpi_i = \varpi_i - \varpi_{Beagle}$ at this stage of our research. We therefore concentrate our effort first on the convergence of $\Delta\Omega_i = \Omega_i - \Omega_{\rm Ref}$, which is the difference between the longitudes of the nodes of a given asteroid and that of a reference orbit. To obtain a preliminary estimate of the Beagle family age, we computed a χ^2 -like variable of the form:

$$\chi_0^2 = \sum_{i=2}^{N_{ast}} (\Delta\Omega_i^2), \tag{6}$$

where $N_{\rm ast}$ is the number of family members, and angles are expressed in radians, so that χ_0^2 has dimensions of rad^2. First, we estimated thee minimum values of χ_0^2 for the OUT part of the Beagle family, for the cases when i) (656) Beagle and ii) (1687) Glarona are taken as reference orbits. The statistical error σ of the best-fit convergence solution can then be estimated using Carruba et al. (2018):

$$\sigma^2 = \frac{(\chi_0^2)_{\rm min}}{N_{\rm DF}}, \tag{7}$$

where N_{DF}, the number of degrees of freedom, is equal to $N_{ast} - 2$, since there are $N_{ast} - 1$ angles differences and one estimated parameter (the family age). Once values of the errors are obtained using Eq. (7), a proper χ^2 variable can then be computed using the relationship:

$$\chi^2 = \sum_{i=2}^{N_{\rm ast}} \left[\left(\frac{\Delta\Omega_i}{\sigma} \right)^2 \right]. \tag{8}$$

The age of the family and its uncertainty can then be computed using standard least-squares statistics. For this purpose, we calculate $\Delta\chi^2 = \chi^2 - \chi^2_{\rm min}$, where $\chi^2_{\rm min} \simeq 1$. The formal best-fit solution corresponds to the epoch for which $\chi^2 = \chi^2_{\rm min}$. The confidence level of this solution is determine by an appropriated choice of the $\Delta\chi^2$ value. Assuming that χ^2

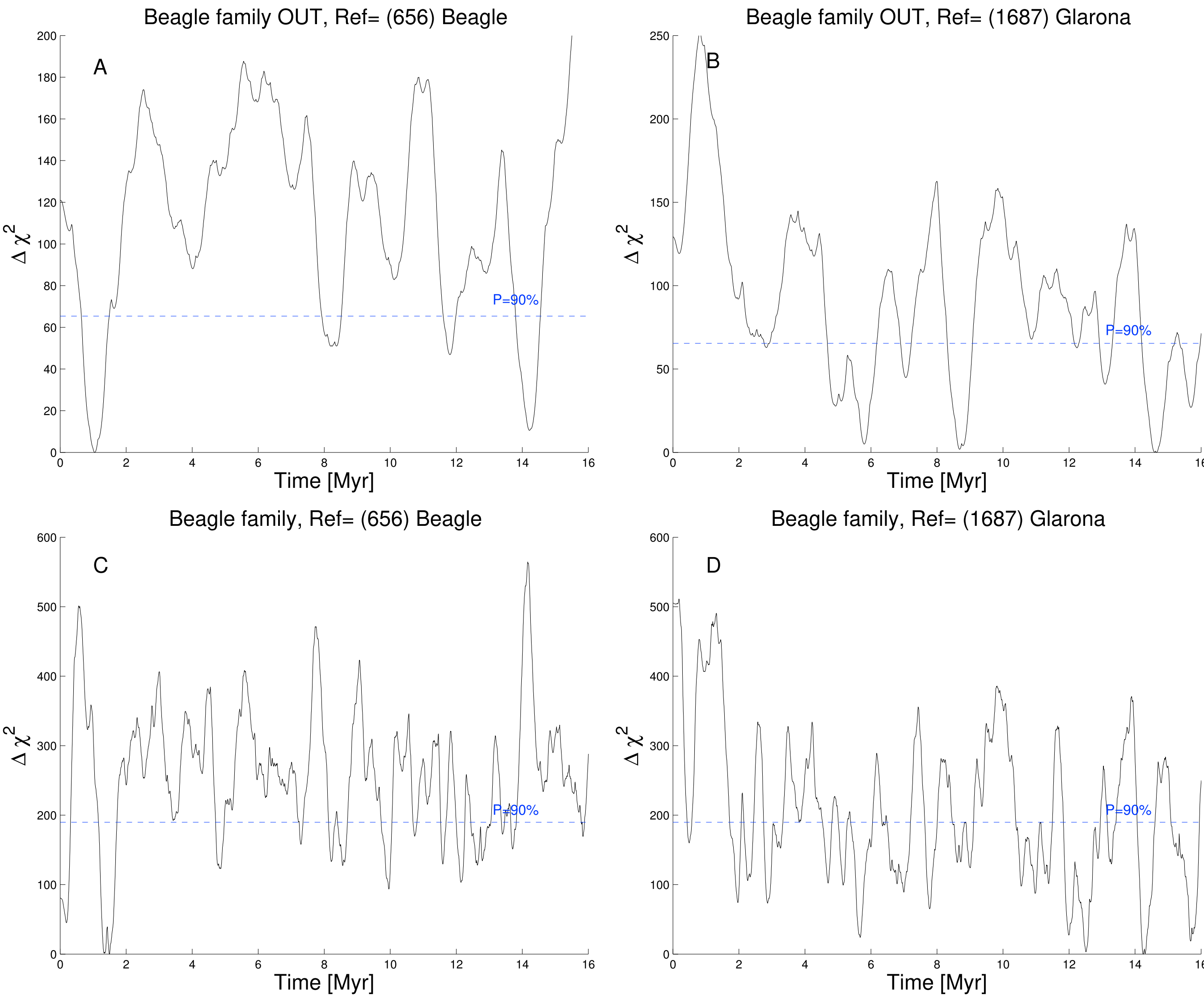

Fig. 10. The time dependence of the χ^2 variable of Eq. (7) for the OUT Beagle family, using (656) Beagle as a reference (panel A) or using (1687) Glarona as the OUT subset (panel B). The horizontal line displays the 90% probability confidence level. Panels C and D shows the same, but for the whole Beagle family.

of Eq. (7) follows the cumulative distribution function of a χ^2 variable (see for instance Eq. (6) of Carruba et al. (2018)), for given values of N_{DF} and of a probability confidence level (90% in this work) it is then possible to compute the appropriate $\Delta\chi^2$ for the given problem. We applied this procedure to the whole Beagle family and to the OUT sub-set, using either (656) Beagle, (1687) Glarona or other asteroids as reference orbits. Our results are shown in Fig. 10.

We could not find a well-defined $\Delta\chi^2$ minimum for any of the studied cases, that would all be classified as "type-B" solution in the qualitative analysis performed by Carruba et al. (2018b). Generally speaking, both results for the OUT and for the whole family have more acceptable solutions for the case when (1687) Glarona is taken as a referene orbit, which may suggest that this body is a better candidate for being the family parent body. Minima of $\Delta\chi^2$ in this case tend to occur for ages longer than 14 Myr, and would tend to confirm the analysis of Nesvorný et al. (Nesvorný, 2008). However, in all cases the estimated values of σ are of the order of 85° or more, which is not a good error level for this kind of method (previous results for other families (Carruba et al., 2018; Carruba et al., 2018b) yielded $\sigma \simeq 40°$). Overall, this analiysis is compatible with an age of $\simeq 14$ Myr and (1687) Glarona as a parent body, but results are not conclusive enough to positively reach this conclusion.

To further investigate this issue, we then performed a simulation that also includes the effect of the non-gravitational Yarkovsky force. Since no information is available on the spin orientation of any member of the Beagle family, for each family member we created 71 clones with da/dt values uniformly sampling a range between minimum and maximum estimated drift-rates. We used as maximum rate the value $1.5 \times 5.5 \cdot 10^{-10}$ au/d, where $5.5 \cdot 10^{-10}$ au/d is a typical value of drift rate for C-type families (Spoto et al., 2015), and 1.5 is a factor accounting for the uncertainty by which key parameters such as the asteroid density and thermal conductivity are known.

We integrated backward in time our sample of Beagle clones, using `SWIFT_RMVS3_DA` , a code derived from the `SWIFT_RMVS3` package in the swift-family which has an additional implementation of the Yarkovsky effect, as described in Nesvorný & Bottke (Nesvorný and Bottke, 2004). Orbital elements and their difference with respect to the reference orbit were digitally filtered with the same procedure described for the conservative simulation. At each time step we then selected the clone of each particle that showed the best convergence with respect to the reference orbit.

The time dependence of the $\Delta\chi_0^2$ variable of Eq. (6) for the OUT Beagle

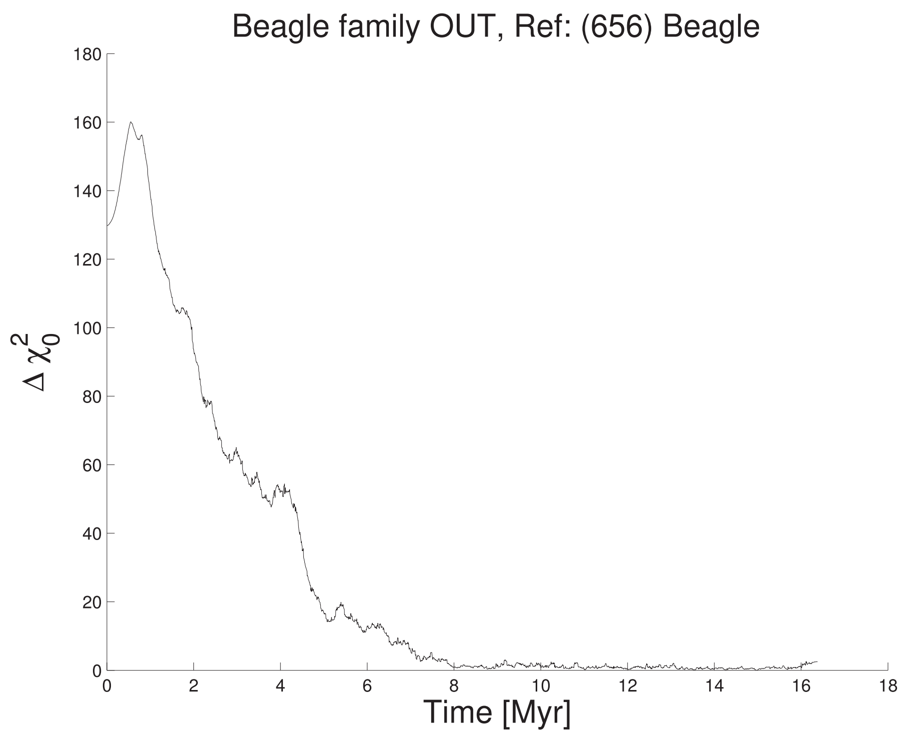

Fig. 11. The time dependence of the $\Delta\chi_0^2$ variable for the OUT Beagle family, using (656) Beagle as a reference, when the Yarkovsky force is considered.

family, using (656) Beagle as a reference, is shown in Fig. 11. Regrettably, our algorithm authomatically selects whatever clone is closest to the reference orbit at that time and, because of the fast precession of the longitudes of the nodes in the Beagle family region, very low values of χ_0^2 are reached in timescales of the order of 3 Myr or less. Results are similar if we use (1687) Glarona as a reference orbit instead, or if we consider the whole family. Since the Beagle family is probably older than 10 Myr, unless new information become available on the spin states of Beagle family, simulations including the Yarkovsky force will not be able to significantly constrain the family age.

6. Conclusions

Our results could be summarized as follows:

- We identified the membership of the Beagle family using currently available data on asteroid proper elements and Hierarchical Clustering Method. There are currently 180 asteroids in the Beagle family so obtained, 32 more than listed in previous works Nesvorný et al. (2015). Three-body and secular resonances seems to play a minor role in the dynamical evolution of the Beagle family.
- We revised the physical properties of the Beagle family and of asteroids in the local background. The Beagle family is made mostly of C-complex objects, with a very limited presence of possible interlopers from other taxonomic classes.
- We obtained age estimates of the Beagle family using the V-shape method of Spoto et al. (2015) and the Yarko-Yorp Monte Carlo approach of (Vokrouhlický et al., 2006a, 2006b; Carruba et al., 2015). There might be a dichotomy for the estimated age of the IN and OUT portions of the Beagle V-shape, with an estimated age of 90^{+50}_{-30} Myr for the IN part and of 35^{+65}_{-35} Myr for the OUT part, also observed when Spoto et al. (2015) method is applied. These results suggests that either i) the Beagle family may be the outcome of two distinct collisionary events, or that ii) it was the result of an anisotropic break-down or that iii) contaminations from the Themis family may cause larger uncertainties on the age estimates of this secundary family. Neither of these three hypothesis can be verified or excluded at this time.
- We used the Backward Integration Method (BIM) to assess the convergence of secular angles, mostly of the longitudes of nodes, for the IN and OUT subgroups of the Beagle family, and for the family as a whole. The Beagle family may be comatible with an age of $\simeq$ 14 Myr, especially when (1687) Glarona rather than (656) Beagle is taken as a reference for BIM, but results are not conclusive enough to positively reach this conclusion. Results of BIM when the Yarkovsky force is considered only allow to conclude that the family should be older than $\simeq$ 3 Myr, which is in agreement with results from the current distribution of longitudes.

Overall, we were not able to positively confirm a young age estimate for the Beagle family. Results of our method may be compatible with an age of $\simeq$ 14 Myr, but, unless further data is obtained on the Beagle family members obliquities, this result cannot currently be confirmed by BIM when the Yarkovsky force is accounted for. Revising the current age estimate of the Beagle family remains, therefore, an interesting open problem in asteroid dynamics.

Acknowledgments

We are grateful to the reviewer of this paper, Dr. Bojan Novaković, for comments and suggestions that greatly improved the quality of this paper. We would like to thank the São Paulo State Science Foundation (FAPESP) that supported this work via the grant 16/04476-8, and the Brazilian National Research Council (CNPq, grant 305453/2011-4). We acknowledge the use of data from the Asteroid Dynamics Site (AstDys) (http://hamilton.dm.unipi.it/astdys, Knežević & Milani (Knežević and Milani, 2003)). This publication makes use of data products from the Wide-field Infrared Survey Explorer (WISE) and Near-Earth Objects (NEOWISE), which are a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of

Technology, funded by the National Aeronautics and Space Administration.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.pss.2018.08.004.

References

Bendjoya, P., Zappalà, V., 2002. In: Bottke Jr., W.F., Cellino, A., Paolicchi, P., Binzel, R.P. (Eds.), Asteroids III. University of Arizona Press, Tucson, p. 613.
Brož, M., reportThesis, Charles Univ., Prague, Czech Republic.
Carruba, V., Burns, J.A., Bottke, W., Nesvorný, D., 2003. Icarus 162, 308.
Carruba, V., Nesvorný, D., Aljbaae, S., Domingos, R.C., Huaman, M.E., 2015. MNRAS 451, 4763.
Carruba, V., Nesvorný, D., 2016. MNRAS 457, 1332.
Carruba, V., Nesvorný, D., Vokrouhlický, D., 2016. AJ 151, 164.
Carruba, V., Vokrouhlický, Nesvorný, D., 2017. MNRAS 469, 4400.
Carruba, V., Vokrouhlický, D., Nesvorný, D., Aljbaae, S., 2018. MNRAS 477, 1308.
Carruba, V., De Oliveira, E.R., Rodrigues, B., Requena, I., 2018b. MNRAS 479, 4815.
Cellino, A., Michel, P., Tanga, P., Zappalà, V., Paolicchi, P., Dell'Oro, A., 1999. Icarus 141, 79.
DeMeo, F.E., Carry, B., 2013. Icarus 226, 723.
Elst, E.,W., Pizarro, O., Pollas, C., Tichá, J., Tich́y, M., Moravec, Z., Offutt, W., Marsden, B.G., 1996. IAU, Circ. 6456, 1.
Gallardo, T., 2014. Icarus 231, 273.
Hsieh, H.H., Jewitt, D., 2006. Science 312, 561.
Hsieh, H.H., Novaković, B., Yoonyoung, K., Brasser, R., 2018. AJ 155, 96.
Ishihara, D., Onaka, T., Kataza, H., et al., 2010. A&A 514, A1.
34 co-authors Ivezić, Ž., 2001. AJ 122, 2749.
Jacobson, S.A., Scheeres, D.J., 2011. Icarus 214, 161.
Knežević, Z., Milani, A., 2003. A&A 403, 1165.
Levison, H.F., Duncan, M.J., 1994. Icarus 108, 18.
Mainzer, A.K., Bauer, J.M., Cutri, R.M., Grav, T., Kramer, E.A., Masiero, J.R., Nugent, C.R., Sonnett, S.M., Stevenson, R.A., Wright, E.L., 2016. NEOWISE Diameters and Albedos V1.0. EAR-A-COMPIL-5-NEOWISEDIAM-V1.0. NASA Planetary Data System.
Masiero, J.R., Mainzer, A.K., Grav, T., Bauer, J.M., Jedicke, R., 2012. APJ 759, 14.
Milani, A., Cellino, A., Knežević, Z., et al., 2014. Icarus 239, 46.
Nesvorný, D., Morbidelli, A., 1998. AJ 1163, 3029.
Nesvorný, D., Bottke Jr., W.F., Dones, L., Levison, H.F., 2002. Nature 417, 720.
Nesvorný, D., Bottke, W.F., Levison, H.F., Dones, L., 2003. AJ 591, 486.
Nesvorný, D., Bottke, W.F., 2004. Icarus 170, 324.
6 co-authors Nesvorný, D., 2008. AJ 679, L143.
Nesvorný, D., Brož, M., Carruba, V., 2015. In: Michel, P., DeMeo, F.E., Bottke, W. (Eds.), Asteroid IV. Univ. Arizona Press, p. 297.
Novaković, B., Cellino, A., Knežević, Z., 2011. Icarus 216, 69.
Novaković, B., Hsieh, H.H., Cellino, A., 2012a. MNRAS 424, 1432.
Novaković, B., Dell'Oro, A., Cellino, A., Knežević, Z., 2012b. MNRAS 425, 338.
Novaković, B., Hsieh, H.H., Cellino, A., Micheli, M., Pedani, M., 2014. Icarus 231, 300.
Pravec, P., Fatka, P., Vokrouhlický, D., et al., 2018. Icarus 304, 110.
Press, V.H., Teukolsky, S.A., Vetterlink, W.T., Flannery, B.P., 2001. Numerical Recipes in Fortran 77. Cambridge Univ. Press, Cambridge.
Ryan, E.L., Woodward, C.E., 2010. AJ 140, 933.
Sheskin, D.J., 2003. Handbook of Parametric and Nonparametric Statistical Procedures, fourth ed. Elsevier pub.
Spoto, F., Milani, A., Knežević, Z., 2015. Icarus 257, 275.
Sykes, M. V., Icarus, 85, 267.
Vokrouhlický, D., Brož, M., Morbidelli, A., et al., 2006a. Icarus 182, 92.
Vokrouhlický, D., Brož, M., Bottke, W.F., Nesvorný, D., Morbidelli, A., 2006b. Icarus 183, 349.
Vokrouhlický, D., Pravec, P., Durech, J., et al., 2017. A&A 598, A91.
Zappala, V., Cellino, A., Farinella, P., Knezevic, Z., 1990. AJ 100, 2030.