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AGE OF THE VERITAS ASTEROID FAMILY FROM TWO INDEPENDENT ESTIMATES

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Abstract. The family of (490) Veritas is a young, dynamically heterogeneous asteroid family, located in the outer main belt. We took advantage of the fact that it can be decomposed in several groups, in terms of the principal mechanisms that govern the local dynamics, to asses the age of the family. Using the members with the diffusive chaotic motion, we derive an estimate of the age of the family of $\sim$8.9 My, which agrees well with the value of 8.3 My, previously derived by Nesvorný et al. (*ApJ*, 2003), and confirmed here by analyzing the members on regular orbits.

1. INTRODUCTION

Asteroid families originate from the catastrophic collisions among asteroids. A swarm of fragments is created due to a complete/partial breakup of the parent body, or to the formation of a sizeable crater on its surface. Immediatelly after formation a part of the fragments can either escape or reaccumulate; typically, however, many fragments do acquire independent orbits, but stay close enough in the phase space of orbital elements to form a conspicuous group, easily recognizable against the background of non family objects.

The families were discovered by Hirayama (1918) on purely dynamical grounds, but he was also the first to propose that family members are of common origin. Nowadays we know that this is indeed so, and many studies are therefore conducted to reveal their membership, their dynamical and physical characteristics, their role in the overall solar system collisional evolution, etc. To the interested reader we can recommend a number of recently published review papers dealing with dynamical (Knežević et al., 2002; Roig and Beaugé, 2005) and physical (Zappalá et al., 2002; Cellino et al., 2002) properties of the families, problems of their identification (Bendjoya and Zappalá, 2002; Lemaitre, 2005), of newly discovered small-scale structures (Nesvorný et al., 2002), etc.

One of the problems in connection with asteroid families which remained open for a long time is the determination of the age of the families. These ages are important to constrain the collisional evolution models, to understand better collisional physics - e.g. initial velocity fields, to learn more on the mechanical properties of asteroids - internal strength, composition, to study the associated dust bands and their interaction with the Earth, etc.

Some 15 years ago the ages of the families were completely unknown, with only a few order-of-magnitude estimates based on the cratering records, space weathering, and on some equaly uncertain dynamical arguments. Then the first more precise family age determination has been attempted by Milani and Farinella (1994), who introduced the so-called *chaotic chronology* to show that formation of the Veritas asteroid family might have been a comparatively recent event, taking place ≈ 60 My ago. Their work has been further extended and refined by Knežević and Jovanović (1997) and Knežević and Pavlović (2002) who set an upper limit to the age of the Veritas family of ≈ 100 My, but pointing also out that the family may actually be much younger.

An important breakthrough has been achieved only recently with the works of Nesvorný et al. (2002) and Vokrouhlický et al. (2006) who employed original procedures to asses the age of the young and of the old families, respectively. The method suitable for the young families consists in integrating backwards the equations of motion for the family members, until the longitude of the node, Ω, and the argument of pericenter, ω, of their orbits, or at least of some of them, converge to the values they had at the time of break-up. Using this method Nesvorný et al. (2002) estimated the age of the Karin family to some 5.8 My, while Nesvorný et al. (2003) applied the same method to the Veritas family and derived an age for it of ~ 8.3 My. The old asteroid families can be approximately dated, based on the distribution of the family members in the (a, H) plane, where H is the absolute magnitude of a body, and a is the semi-major axis of its orbit. Bodies of diameter $D < 20$ km (large H) undergo significant orbital migration, due to the non gravitational Yarkovsky effect. The amount of Yarkovsky-induced migration is size-dependent, $\Delta a \sim D^{-1}$ (Farinella and Vokrouhlicky, 1999). Thus, as time progresses, families form a characteristic 'V'-shaped distribution in the (a, H) plane. The age of the family can then be approximately found by a method described in Vokrouhlický et al. (2006).

The aim of this paper is to extend the analysis by Knežević et al. (2002), in which a modified chaotic chronology method was used to study the dynamics in the chaotic layer cutting through the region of the phase space of orbital elements occupied by the Veritas family. We derive and compare two independent estimates of the age of the family: (i) an improved estimate based on the backward integrations of dynamically stable members of the family, and (ii) a new estimate based on the accurately determined rates of chaotic diffusion for the family members located in the chaotic strip due to the $(5, -2, -2)$ three-body mean motion resonance (Nesvorný and Morbidelli, 1998).

The tools we used in the study include numerical integration of orbits of family members (100 My) and of fictitious asteroids (10 My), computation of the time series of proper elements and the corresponding Lyapunov times, and determination of the associated diffusion coefficients for the resonances that might have produced measurable effects in the motion of family members over the time scales of interest.

2. THE FAMILY AGE

The recent analysis of the dynamical structure of the Veritas asteroid family by Tsiganis et al. (2006, *in preparation*) reveals that the family can be divided into four dynamically distinct groups, one with remarkably stable motion, another with strongly chaotic motion giving rise to diffusion, and two with an intermediate type of motion (a group with small amplitude, long periodic variations of orbits, and a group with motion corresponding to stable chaos). These different dynamics are due to the fact that family members are either located near or within chaotic strips associated with the mean motion resonances, or they populate more or less stable regions far from the resonant zones.

Only the first two groups were used to estimate the family age. As regards the family members with stable motion, we essentially followed the procedure by Nesvorný et al. (2003). We integrated backwards in time 50 objects for 10 My and calculated their proper elements time series. Next, we calculated the averaged difference of proper nodal longitudes, $\Delta\Omega$, with respect to the largest asteroid in the group, (1086) Nata, as a function of time. A clustering of proper nodes within $31°$ was found at $t = -8.3$ My, in full agreement with Nesvorný et al. (2003), who had, however, found the clustering to within $\sim 40°$. The extended simulation to $t = -100$ My (the upper bound for the age of the family, as proposed by Knežević and Pavlović 2002) did not reveal any other clustering. Our integrations give a more tight clustering of the nodes because (i) we excluded from the calculation the family members with quasi periodic variations of elements, since these bodies are close to the resonances which modulate their nodal frequencies, and (ii) we did the calculation using proper elements, thus reducing the effects of high-frequency variations.

The other estimate of the age of the family has been obtained using a modified method of chaotic chronology for the strongly chaotic group of family members located in the $(5, -2, -2)$ three body mean motion resonance. A resonance can generate chaotic diffusion, which may have appreciable effects even on short time scales, depending on the size of the coefficients and on the degree of overlap between the harmonics of the resonant multiplet. Using our integrations of resonant family members, we calculated the mean squared displacement of the action variables, related to the proper values of e and I ($J_1 \sim \sqrt{a}\, e^2/2$ and $J_2 \sim \sqrt{a}\, I^2/2$) as functions of time, the average being computed over the corresponding set of family members. In the framework of a simple diffusion approximation, the mean squared displacement in an action variable, $\langle(\Delta J_{\rm j})^2\rangle\,(t)$, grows linearly with time, with a characteristic rate that is called *diffusion coefficient*. The diffusion coefficient in each action, $D(J_{\rm j})$, is computed as the least-squares-fit slope of the $\langle(\Delta J_{\rm j})^2\rangle\,(t)$ curve.

We first observed that indeed resonant Veritas family members do undergo a diffusive evolution in the space of proper e and I, the coefficients of diffusion of the corresponding actions being fairly large. Introducing a couple of reasonable assumptions – that the diffusion coefficients are constant throughout the range of e and I

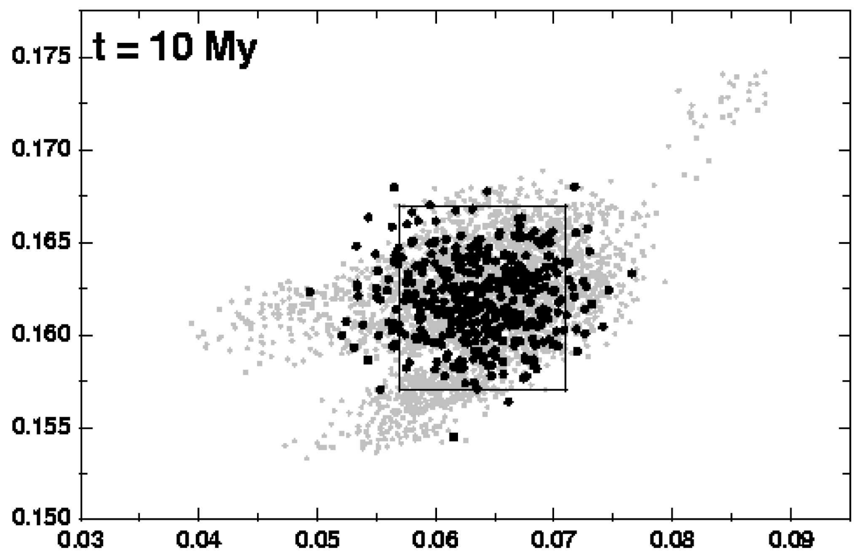

Figure 1: The snapshot in the $(e_p, sinI_p)$ plane, showing the spread of 400 fictitious asteroids after 10 My of evolution. The grey dots are the traces of the real resonant family members that represent the extent of the diffusive zone (as obtained after 10 My of orbit propagation, but starting from the present distribution of real family members, delimited by the box). The black dots are fictitious asteroids that evolved according to our random-walk model assuming the values of the diffusion coefficients to be as in the $(5, -2, -2)$ region. As shown in the plot, our random-walkers cover roughly the same area as the core of the real objects. The object in the upper right corner is an escaper from the family.

spanned by the chaotic objects, and that e and I evolve more or less independently from each other, at least for a while – a simple random-walk model could be used to describe the evolution of proper elements (the validity of the model has been justified by the fact that the current distribution of J_1 for resonant members is well fitted with a Gaussian, thus implying normal diffusion). Starting from an initial distribution nearly a δ-function in e and $\sin I$, at every Δt, each body undergoes a random 'jump', whose length in J_1 and J_2 is given by a 2-D Gaussian distribution. The values of $D(J_1)$ and $D(J_2)$ correspond to the standard deviation of the projections of the probability density, along the J_1 and J_2 axis, respectively.

Next, we produced a series of snapshots of the evolution of a fictitious initial distribution of 400 $(5, -2, -2)$-resonant bodies in the $(e_p, \sin I_p)$ space, according to our random-walk model, to verify that the fictitious objects indeed spread diffusively in action space, the dispersion growing linearly with time. At $t \sim 10$ My we found that the spread of the fictitious population in the space of proper elements is slightly wider than the present spread of the real family members (Fig. 1). If the family were much older than the considered interval, the observed distribution in the resonance would have been much more extended, or the resonance would have been heavily depleted with respect to the non-resonant population. On the other hand, using the value of the diffusion coefficient and the standard deviation of the Gaussian distribution of J_1 action, we calculated that the age should be 8.9 My. Thus, assuming normal diffusion and applying a simple random walk approach we established that the age of the chaotic group is ~ 8.9 My, a result compatible with the age of the family deduced from the analysis of the group of family members with regular motion.

Nesvorný et al. (2003) considered the possibility that the 8.3 My age estimate may be due to a secondary break-up within the Veritas family, responsible for the formation of a tight group of bodies around (1086) Nata. In that case the 8.3 My estimate would correspond not to the age of the whole family but to that of this secondary group. Although it cannot be ruled out, a double break-up within ~ 50 My seems unlikely. Our result suggests that the group of regular bodies and the group of chaotic bodies were most likely formed at the same time.

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