

VERITAS ASTEROID FAMILY STILL HOLDS SECRETS?

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Abstract. Veritas asteroid family has been studied for about two decades. These studies have revealed many secrets, and a respectable knowledge about this family had been collected. Here I will present many of these results and review the current knowledge about the family. However, despite being extensively studied, Veritas family is still a mystery. This will be illustrated through the presentation of the most interesting open problems. Was there a secondary collision within this family? Does asteroid (490) Veritas belong to the family named after it? How large was the parent body of the family? Finally, some possible directions for future studies that aims to address these questions are discussed as well.

1. INTRODUCTION

Asteroid families are groups of objects, believed to be born in the catastrophic disruption of single parent bodies. Families are usually identified in the space of proper orbital elements (Milani & Knežević 1990, 1994): proper semi-major axis (a_p), proper eccentricity (e_p), and proper inclination (I_p). The orbital elements describe the size, shape and tilt of orbits. Proper elements, which are more constant over time than instantaneous osculating orbital elements, provide a dynamical criterion of whether or not a group of bodies has a common origin. So far, ejecta from a several tens of collisions have been discovered in the main asteroid belt (see e.g. Zappalà et al. 1994; Mothe-Diniz et al. 2005; Novaković et al. 2011).

The study asteroid families is a very important for many reasons. It is difficult to find a line of research in asteroid science that does not lead sooner or later to problems related to families. Let us to mention here only a few important topics.

These groups are unique *natural laboratories* to analyze the outcomes of high-energy collisions (Zappalà et al. 2002; Michel et al. 2003; Durda et al. 2007). The size and velocity distributions of the family members provide important constraints for testing our understanding of the physics involved in the breakup process.

Spectroscopic observations of family members in order to characterize their plausible mineralogical composition, provide a unique opportunity to obtain information on the inner layers of their parent bodies. Thus, this allow one to use families to study the mineralogical structure of various parent bodies (Cellino et al. 2002).

The number of identified families, along with their ages and sizes of parent bodies, is an important constraint to model the collisional history of the main asteroid belt (Bottke et al. 2005).

Last but not least, the collisional asteroid families are known to be one of the main sources of the Near Earth Asteroids (NEAs), because the violent collisions among the asteroids inject a significant number of fragments into the powerful resonances, which are then responsible for transport of these bodies inside the region of the terrestrial planets. Thus, by studying an asteroid family one can get better insights in some NEAs as well.

However, erosion and dynamical evolution of the orbits over time can alter the original signature of the collision. Nowadays, it is well known that the kinematical structures of asteroid families evolved over time, with respect to the original post-impact situations, as a result of chaotic diffusion and gravitational and non-gravitational perturbations (Milani & Farinella 1994; Bottke et al. 2001; Carruba et al. 2003; DellOro et al. 2004). These mechanisms changed the original shapes of the families produced in collisions, and consequently complicated the physical studies of high-velocity collisions. For these reasons young families (< 10 Myr) are particularly important to study.

The Veritas family is particularly interesting to study for many reasons. It is a young asteroid family which contains both, regular and chaotic members. Next, it is identified as a source of prominent interplanetary dust band and linked to one of the largest increase in cosmic dust deposit on the Earth. Also, being young and located in the outer belt, it is a good place to search for main belt comets¹ (MBCs). Finally, a recent study suggested that asteroid (490) Veritas itself is a possibly interloper.

Despite being young, and one of the best studied with many published papers devoted to it, this family is so complex, that we still did not reveal all its secrets. Aim of this paper is to give a review of our current knowledge about Veritas family, but also to indicate some still open problems, and to try to give some ideas for possible solutions to these problems.

2. VERITAS FAMILY: WHAT WE KNOW ABOUT IT

In this Section we describe the most important characteristics of the Veritas family, including its structure in the space of proper elements, dynamical characteristics in the phase space occupied by its members, physical characteristics of asteroids that belong to it, and, finally, the age of the family.

2.1. DYNAMICAL CHARACTERISTICS, MEMBERSHIP AND STRUCTURE

The Veritas family is a comparatively small and compact one, located in the outer belt. The dynamics of this region, and its influence on the structure of the family are very well studied (see for example Milani & Farinella 1994; Knežević & Pavlović 2002; Nesvorný et al. 2003; Tsiganis et al. 2007, Novaković et al. 2010). From dynamical point of view, Veritas family occupies a very interesting and complex region, crossed by several moderate 2- and 3-body mean motion resonances (MMRs).

The reliability of its membership is rated as a very high (Zappalà et al. 1995), and also Migliorini et al. (1995) estimated that the probability of chance to find interlopers in this family is negligible small. Let us to describe here briefly the dynamical

¹Main belt comets are bodies with asteroid-like dynamical properties but comet-like physical properties (Hsieh & Jewitt 2006). These are dynamically ordinary main-belt asteroids on which, probably, subsurface ice has recently been exposed (e.g. because of a collision).

characteristics using an updated definition of the family membership. By applying the well known Hierarchical Clustering Method (HCM) (Zappalà et al. 1990) to the catalog of synthetic proper elements (database as of September 2011), we linked 876 asteroids with the Veritas family, for a velocity cut-off of $v_c = 40$ m/s as in Tsiganis et al. (2007). The structures of the family in the (a_p, e_p) and $(a_p, \sin I_p)$ planes are shown in Figs. 1. and 2.

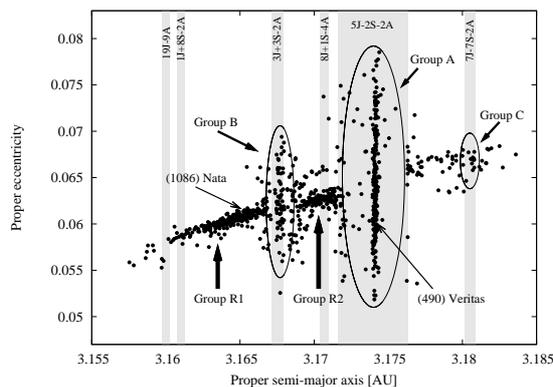


Figure 1: Members of the Veritas family shown in the (a_p, e_p) plane. The ellipses denotes three different groups of unstable bodies. The vertical dashed areas represent approximate locations of the main MMRs, as indicated by the corresponding labels. Locations of two largest asteroids, namely (490) Veritas and (1086) Nata are shown as well.

The main characteristics of the family remain the same as in previous studies, except the fact that family now spreads across the 19J/9A resonance.

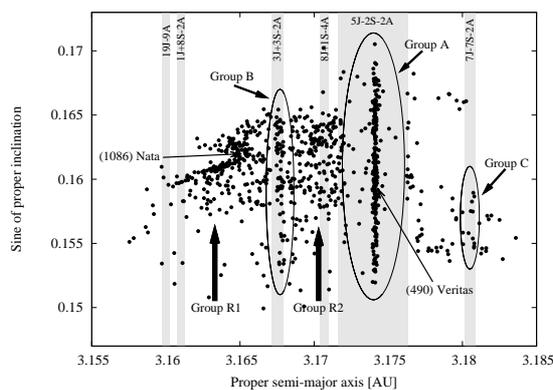


Figure 2: The same as in Fig. 1., but in the $(a_p, \sin(I_p))$ plane.

The most important role for the dynamics in the region occupied by Veritas family members play two 3-body MMRs, namely (5J-2S-2A) and (3J+3S-2A). The main

chaotic zone is located around 3.174 AU and it is associated with the action of the (5J-2S-2A) resonance. The family members that reside in this resonance² are characterized by very short Lyapunov times (less than 10 kyr), and can be dispersed over the observed range in e_p and $\sin I_p$ on a ~ 10 Myr time-scale. Also, due to this resonance the motion of asteroid (490) Veritas is strongly chaotic. On the other hand, despite obviously causes some instabilities the (3J+3S-2A) resonance induces much less chaos than the (5J-2S-2A). The lower values of Lyapunov times for bodies inside this resonance are about 30 kyr.

In addition, the Veritas family is also crossed by the (1J+8S-2A), (8J+1S-2A) and (7J-7S-2A) 3-body MMRs, but these three resonances do not give a rise to significant instabilities. The same applies to two 2-body MMRs, 21J/10A and 40J/19A (not shown in Figs. 1. and 2), identified by Milani et al. (1997).

Apart from the unstable regions, within the borders of Veritas family, there are at least two regions characterized by stable orbits. These are the regions denoted as R_1 and R_2 in in Figs. 1. and 2.

2. 2. SPECTRAL CHARACTERISTICS AND SIZE OF PARENT BODY

Among the most important characteristics of each family are spectral ones. First spectroscopic analysis of asteroids that belong to Veritas family was performed by di Martino et al. (1997). These authors observed seven members of the family, namely the asteroids (490) Veritas, (844) Leontina, (1086) Nata, (2428) Kamenyar, (2934) Aristophanes, (5592) Oshima, and (7231) Porco. In addition these observations also included a possibly family member, the asteroid (5107) 1987 DS_6 . The obtained spectra showed a surprising slope gradient spanning from 0 to about 8%, a range which includes the slopes characteristics of all the low albedo primitive bodies (from C to D -type, in terms of Tholens taxonomy). This unexpected result was explained by the presence of thermally altered large asteroids among the outer belt population.

Analyzing the asteroids taxonomy derived from reflectance spectra obtained by two large visible spectroscopic surveys, the SMASS II (Bus & Binzel 2002) and the S^3OS^2 (Lazzaro et al. 2004), Mothé-Diniz et al. (2005) found 8 members of the Veritas family with know spectra. All of them belong to the C complex: 6 Ch class, 1 C class, and 1 Cg class. This homogeneity was in contrast with the findings of di Martino et al. According to Mothé-Diniz et al. (2005) there are two main reasons for this difference.

First, the list of family members used by di Martino et al. (1997) included objects which were not classified as members of the family by Mothé-Diniz et al. (2005). In particular, (844) Leontina and (5107) 1987 DS_6 . The spectra of these asteroids correspond to the X or D types, which is rather compatible with the dominant taxonomy in the background.

Second, for some asteroids Mothé-Diniz et al. found remarkable differences between the spectra presented by di Martino et al. and the spectra published by the main surveys they considered. This was the case of (490) Veritas and (2428) Kamenyar (observed by the SMASS II) and (5592) Oshima (observed by the S^3OS^2), which appear to be X/D type bodies in di Martino et al. (1997) but were classified as Ch class asteroids by the above surveys. These differences maybe due to actual

²This is the group of bodies (Group A) that was used by Tsiganis et al. (2007) and Novaković et al. (2010), to compute the age of Veritas family.

inhomogeneities in the bodies' surface or they should be attributed to problems on the processing of the observational data.

Also very important characteristic to know about an asteroid family is a size of its parent body. Simply by summing the volumes of all known family members at that time, Nesvorný et al. (2003) estimated that diameter of the parent body of Veritas family was about 140 km.

Later, Durda et al. (2007) investigated the size-frequency distributions (SFDs) resulting from impacts into 100-km-diameter parent asteroids, using a SPH/N-body simulations. Then, these modelled SFDs were used to scale to targets, both larger and smaller than 100 km, in order to estimate the size of parent bodies of families. In this way they found a diameter of Veritas parent body was 177 km.

Both estimations however are made assuming asteroid (490) Veritas belongs to the family named after it. If this is not the case (see next Section), this would seriously affect these results.

2. 3. AGE OF THE FAMILY

Speaking about the age, more or less, it was clear from the beginning of its study, that Veritas is a young family. The first determination of its age was performed by Milani & Farinella (1994) who found it is not more than 60 Myr old. This age estimation was obtained by integrating family members for 72 Myr backward in time, and showing that the largest member, asteroid (490) Veritas, escapes from the family after about 60 Myr. Later, using the same methodology but more family members and clones, Knežević & Pavlović (2002) were able only to set an upper limit to 100 Myr.

More accurate age determination was obtained at the beginning of XX century. Applying the so-called backward integration method (BIM) to regular bodies from R1 and R2 groups Nesvorný et al. (2003) found that Veritas family is 8.3 ± 0.5 Myr old. This result agrees very well with the result of Farley et al. (2006), who found a transient increase in the flux of interplanetary dust which began at 8.2 ± 0.1 Myr ago, reached a maximum of about 4 times pre-event level, and dissipated over about 1.5 Myr. The terrestrial interplanetary dust particles accretion rate was overwhelmingly dominated by Veritas family fragments during the late Miocene.

The result obtained by Nesvorný et al. (2003) was confirmed by Tsiganis et al. (2007) who developed a statistical version of the method of chaotic chronology (MCH). By applying this method to bodies from Group *A* Tsiganis et al. (2007) estimate the age of Veritas family to be 8.7 ± 1.7 Myr. Later, this was also confirmed by Novaković et al. (2010) who used an improved version of the MCH which takes into account also local oscillations in the diffusion speed to estimate age of the family and got 8.7 ± 1.4 Myr.

It is interesting to note here that at the time of analysis performed by Nesvorný et al. (2003) and Tsiganis et al. (2007) the part of Veritas family located at $a_p > 3.18$ AU was not discovered. This group was firstly linked to the family in the work of Novaković et al. (2010). As many of the asteroids from this region are on regular orbits we check here whether or not it is possible to find a conjunction of nodal longitudes for these objects as well. Indeed, by applying the BIM to 13 regular members of Veritas family located at $a_p \geq 3.18$ AU we found that such clustering occurs at -8.2 Myr, i.e. close to the time estimated to be a moment of family formation (see Fig. 3).

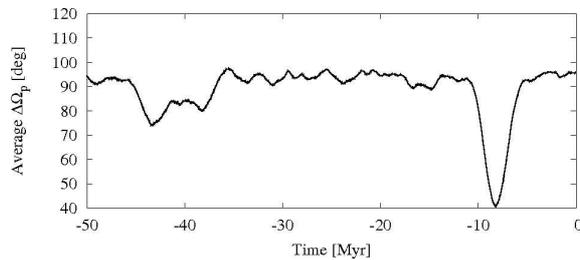


Figure 3: Average differences $\langle \Delta \Omega \rangle$ of the nodal longitudes for 13 members of the Veritas family located at $a_p > 3.18$ AU.

3. VERITAS FAMILY: WHAT WE DON'T KNOW

Due to the complex dynamics associated with the Veritas family, both the family membership and the original positions of the members are not reliably known, despite its young age.

Probably the most serious problem is whether or not asteroid (490) Veritas belong to the family named after it. Recently Michel et al. (2011) performed different numerical simulations of catastrophic disruption of a 140-km-diameter parent body, in order to reproduce SFD of Veritas family members. However, they was not able to produce satisfactorily the estimated size distribution of real family members. On the other hand, these authors also performed similar simulations assuming asteroid (490) Veritas does not belong to the family. In this case the parent body was 112 km in diameter. Remarkably, the outcome of these simulations match perfectly that of the real family, when a porous parent body was assumed. In this case both the size distribution and the velocity dispersion of the real family (but without (490) Veritas) were very well reproduced. This is consistent with the spectral *C*-type of family members, which suggests that the parent body was porous. From these results Michel et al. concluded that it is a very likely that the asteroid (490) Veritas and probably several other small members do not belong to the family as originally defined, and that the definition of the family should be revised. In addition to exact family membership this problem implies that we do not know reliably what was the size of the parent body, and consequently m_{LR}/m_{PB} ratio.

Another open problem is related to the spread of the Group *B* bodies, which correspond to the (3J+3S-2A) resonance. As was noted by Tsiganis et al. (2007) and Novaković et al. (2010), this spread could not be complexity explained by chaotic diffusion. Although some diffusion in this region exists, the time scale to disperse asteroids from this group to their present locations, is about one order of magnitude longer than the estimated age of the family. Thus, the reason for this spread remains unclear.

4. DISCUSSIONS AND CONCLUSIONS

Despite many grate results about Veritas family, obviously some mysteries still exist. One interesting idea which might explain at least some of the problems is that secondary collision took place between family members shortly after formation of

the family (K. Tsiganis, private communication). The distribution of Veritas family members in the $(\sin I_p, H)$ plane has an interesting feature. Most of the asteroids located at $\sin I_p \leq 0.157$ have $H \geq 13$ mag, while significant fraction of asteroids at $\sin I_p \geq 0.157$ have $H \leq 13$ mag (see Fig. 4). This might be an indication about the possible presence of two asteroid families (or about the secondary collision). However, it should be noted that two largest asteroids (490) Veritas and (1086) Nata have both $\sin I_p$ above 0.157.

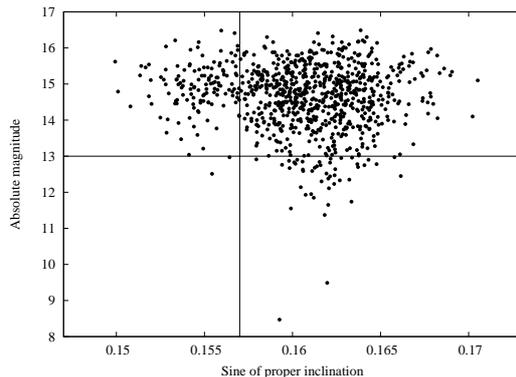


Figure 4: Members of the Veritas family shown in the $(\sin I_p, H)$ plane.

There are also other possibilities. For example, the results of Michel et al. (2011) were obtained using impacting speed of 3 or 5 km/s. This is typical relative velocity among the main belt objects (Bottke et al. 1994). However, the higher impact speeds could not be ruled out. Such an impact would probably involve a high-inclination body. In this case even an impact speed of about 10 km/s would be possible. In order to rule out this scenario we need to understand better this kind of impacts by studying the real families among population of high- i asteroids (Novaković et al. 2011) and to compare these results with the numerical simulations (Michel et al. 2003; Durda et al. 2007).

Recently, Ziffer et al. (2011) compared obtained near-infrared (0.8-2.4 μ m) spectra of two low albedo C complex outer-belt asteroid families: Themis and Veritas. Although they found striking difference between these two families, the results for two potential Veritas family members, asteroids (490) Veritas and (1086) Nata were almost identical, suggesting both surfaces are quite young. Finally, the latest result comes from the WISE data (Masiero et al. 2011), where albedos for 360 potential Veritas family members are provided. The distribution of albedos of these objects as a function of the proper semi-major axis is shown in Fig. 5. The further analysis about possible preferable locations for objects of lower/higher albedo may help to resolve at least some of the mysteries related to the Veritas family.

In any case, the Veritas asteroid family (or what ever should be its name) still holds some secrets and definitely deserve further investigations.

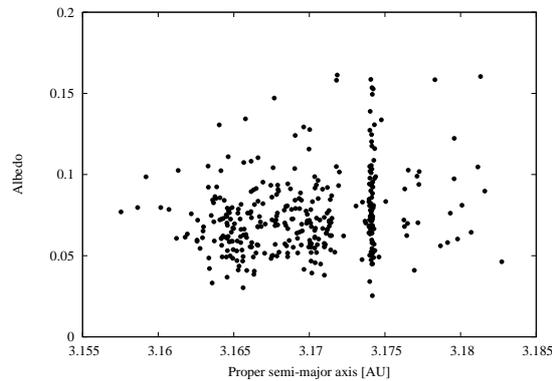


Figure 5: The distribution of albedos for 360 Veritas family members as a function of the proper semi-major axis.

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