Time evolution of the Vesta Family with and without the Yarkovsky effect

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We selected 21103 Vesta Family Members (VFMs) from 371698 numbered and 95836 multi-opposition asteroids with their proper elements using the Hierarchical Clustering Method. Next we studied time evolution of the orbits of all asteroids classified as the VFMs up to 100 My forward from now with and without the Yarkovsky effect. It has been found that the mean drift rate of major semiaxis da/dt of all VFMs is close to 0.01×10^{-4} au My^{-1} for the case without YE and it is equal to -0.10×10^{-4} au My^{-1} for the case with YE.

1 Hierarchical Clustering Method (HCM) applied for searching the Vesta Family Members (VFMs)

We applied the catalogues of the AstDys proper elements[1] actualized at 2014-08-27. They contain proper elements of 371698 numbered asteroids up to the asteroid with the number 404943 as well as the proper elements of 95836 multi opposition asteroids up to the asteroid 6510P-L. So, our database contains 467534 objects totally. In order to select from this set of the Vesta family members (VFMs) we used the Hierarchical Clustering Method (HCM). Numerical procedure applied in this paper is the same as in our previous papers (Włodarczyk & Leliwa-Kopystyński (2014), Leliwa-Kopystyński et al. (2009)). A crucial parameter that appears in the HCM is so called cutoff velocity v_{cut}. We have fitted $v_{cut} = 53$ m/s and for this value we have identified 21103 VFMs (interlopers are not eliminated).

2 Starting data of the VFMs

Apart of the orbital parameters of the individual asteroids there is a set of physical data that is necessary for performing calculations by means of the HCM and to present them versus size of the asteroid family members. Some additional parameters are required to consider the YE as one of the causes of evolution of the asteroid orbits through the time (in parentheses there are the values for Vesta itself):

$\rightarrow H$ (4.20) - the absolute magnitudo, according to the catalogue IRAS-A-FPA-3-RDR-IMPS-V6.0.

$\rightarrow p_v$ (0.423) - the visual geometric albedo according to the catalogue IRAS-A-FPA-3-RDR-IMPS-V6.0. It is assumed that all VFMs have albedo equal to Vesta.

$\rightarrow R$ (2.65×10^5 m) - the radius that is calculated by means of formula: $2R = 1329 \times 10^{-H/5} p_v$[km].

[1] http://hamilton.dm.unipi.it/astdys/index.php?pc=5

$\rightarrow \rho$ (3456 $\mathrm{kg\,m^{-3}}$) - the mean density. It is assumed that all VFMs have density equal to that of Vesta.

$\rightarrow \rho_s = 1500\ \mathrm{kg\,m^{-3}}$ - the mean near-surface density of all VFMs. Arbitrary adopted.

$\rightarrow K = 0.01\ \mathrm{W\ m^{-1}\ K^{-1}}$ - the heat conductibility of the near-surface layer of all VFMs. We adopted this value from Broz site[2]

$\rightarrow C = 680\ \mathrm{J\ kg^{-1}\ K^{-1}}$ - the specific heat of the near-surface layer of all VFMs. We adopted this value after Carruba et al. (2005).

$\rightarrow C_s = (1360\ \mathrm{J\ m^{-2}\ s^{-1}}/(\mathrm{a\ \ in\,au})^2$ - the adopted value of the mean solar constant for an asteroid with the major semiaxis a.

The spin parameters have to be used in calculations as well. They are the rotation period P and the orientation of the rotation axis (its inclination and azimuth) in the ecliptic reference frame. Only these for Vesta are known. The inclinations and the azimuths for the others VFMs are randomly selected. Their rotation periods were adopted from Broz[2].

3 Time evolution of the orbital elements of the VFMs without and with the Yarkovsky effect

The starting orbital elements of 21103 VFMs and planets for the same epoch, were computed with the use of the software Mercury (Chambers, 1999), and added as input files to the software Swift, *swift_rmvs3_f* and *swift_rmvs3_f_y* from Broz[2] which allow us to compute time evolution of orbital elements of VFM without and with the Yarkovsky effects, respectively. Integration was performed 100 My forward.

In Fig.1 radius dependence is well visible especially in positions in semimajor axis. Smaller asteroids have more extended semimajor axes on the both sides of the position of the semimajor axis of the asteroid (4) Vesta.

According to Table 11 in Hardersen et al. (2014) the age of the VF is at least of about 1 Gy. Hence, from our computations, it follows that the maximum changing rate of semimajor axes of the VFMs with the radii greater than 1000 m is about 2×10^{-4} au $\mathrm{My^{-1}}$. We suppose that dispersion of semimajor axes is due to the YE.

According to our computed time evolution of mean (a, e, i) of VFMs during 100 My forward integration without the YE and with the YE, the swarm of VFMs goes to greater values of semimajor axes in mean of about 1.1×10^{-5} au $\mathrm{My^{-1}}$. It has been found that the changes of major semiaxis are equal to 1.1×10^{-5} au $\mathrm{M}y^{-1}$ for the case with YE and they are close to 0.1×10^{-5} au $\mathrm{My^{-1}}$ for the case without YE, i.e. mean value of da/dt connected with the YE is about of -1.0×10^{-5} au $\mathrm{M}y^{-1}$ and hence, probably most of the VFMs have retrograde rotation.

4 Time evolution of orbital elements of selected Vestoids

We put special attention in eight asteroids belonging to the Vestoid class considered by Hardersen et al. (2014). The asteroids are: (3867) Shiretoko, (5235) Jean-Loup, (5560) Amytis, (6331) 1992 FZ1, (6976) Kanatsu, (17469) 1991 BT, (29796) 1999 CW77, and (30872) 1992 EM17. The meteorites Howardite-Eucrite-Diogenite (HED) are their meteorite analogs. Hardersen et al. (2014) suggest that some Vestoids belong to the VF, however some others to the Flora Family. From our 1 Gy forward integration it was appeared that are differences in time evolution of the mean semimajor axis for

[2] http://sirrah.troja.mff.cuni.cz/ mira/mp/

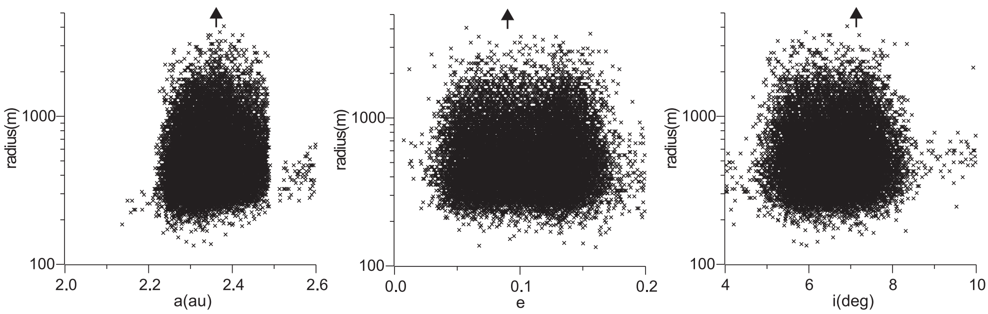

Fig. 1: The radii of the VFMs within the limited range of orbital elements vs. their initial orbital elements (*a, e, i*). Figure illustrating final positions (with or without the YE) of the VFMs is virtually very similar to that presented here. Therefore, presentation of the final (after 100 My) orbital parameters on the same panels would make them unclear. Arrows indicate position of the asteroid (4)Vesta.

all Vestoids. In most of Vestoids the YE decreases value of semimajor axis, in mean of about 4×10^{-7} au My^{-1}. It is a smaller value of semimajor drift that in the case of typical NEOs [(101955) Bennu and (99942) Apophis]. It is connected mainly with the greater value of diameter of these Vestoids - typically of about 5 km, and the greater distance to Sun. Mean diameter of all Vesta Family Members without the asteroid (4) Vesta is 1.2 km.

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