On the V-type asteroids outside the Vesta family 2

The role of close encounters with 4 Vesta: the case of 2704 Julian Loewe

V. Carruba¹, S. Ferraz-Mello¹, T. A. Michtchenko¹, F. Roig², and D. Nesvorný³

¹ IAG, Universidade de São Paulo, São Paulo, SP 05508-900, Brazil
 e-mail: valerio@astro.iag.usp.br
² Observatório Nacional, Rio de Janeiro, RJ 20921-400, Brazil e-mail: froig@on.br
³ Southwest Research Institute, Department of Space Studies, Boulder, Colorado 80302
 e-mail: davidn@boulder.swri.edu

Received ?; accepted ?

Abstract.
 Bla Bla.

Key words. Minor planets, asteroids; Celestial mechanics

1. Introduction

In a previous article of this series we discussed the problem of V-type asteroids outside the Vesta family. V-type asteroids are usually associated with a basaltic surface composition (McCord 1970, Bus 2002, Duffard et al. 2004). Until the discovery of 1459 Magnya (Lazzaro 2000) and of several V-type NEAs (Bus and Binzel 2002 and references within), the only known V-type asteroids were members of the Vesta family. Recently Florczak et al. 2002 discovered two inner belt asteroids located well outside the edges of the family (809 Lundia and 956 Elisa) that show a V-type spectrum. Today 22 V-type asteroids not member of the family are known in the inner belt (Fig. 1, see Table 2 in Carruba et al. 2005 for the asteroid identification). Most of these asteroids have orbits corresponding to ejection velocities with respect to 4 Vesta larger than 1 km/s, which is the maximum possible ejection velocity supposed to be produced in the cratering event. Moreover, most of these objects have orbits that differ from those of current Vesta family members because of their proper \( e \) and \( i \), not because of their \( a \). A simple diffusion via Yarkovsky effect, which mostly change the asteroid semimajor axis, could not explain their current orbital configuration.

In Carruba et al. 2005 we investigated the possibility that asteroids migrated by the combined effect of chaotic diffusion in nonlinear secular resonances and the Yarkovsky effect, and we show how this mechanism could explain the current orbital location of 956 Elisa and 809 Lundia. In this article we study another possible mechanism of dynamical migration: close encounters of family members with 4 Vesta itself. Nearly all bodies in the asteroid belt cross the orbits of 1 Ceres, 2 Pallas, 4 Vesta, or 10 Hygiea, and some approach them closely. When mutual encounter velocities are low, the trajectory of a small body making a close fly-by of these much larger asteroids can be gravitationally deflected, with a consequent change in its heliocentric orbital elements. While the probabilities and typical mutual velocities of such encounters are well understood (Farinella and Davis 1992; Bottke and Greenberg 1993), only a few recent studies have been carried out on their long-term effects (Nesvorný et al. 2002, Carruba et al. 2003).

While the effect of a single encounter might be small, repeated close encounters with large asteroids can produce long term changes in asteroids proper elements. Also, contrary to the Yarkovsky effect, that mostly modify the asteroid semimajor axis and is inversely proportional to the size, close encounters with massive asteroids are size-independent and are able to significantly modify the proper \( e \) and \( i \) of bodies. This mechanism, therefore, could in principle have scattered some of the past family members to the orbits of the current V-type asteroids outside the family, in the inner belt.

Here we investigated the role that close encounters may have played in changing the proper \( e \) and \( i \) of past family members. Also, working on the same hypothesis of Carruba et al. 2005, we investigate the case of 2704 Julian Loewe, and try to determine if evolution in two nonlinear secular resonances \( (s - s_4 + g_6 - g_5, \sigma_6 \) hereafter, and \( s - s_4 + g_6 - g_7, \sigma_7 \) hereafter, where \( s_i \) and \( g_i \) stands for the planetary frequencies of node and pericenter precession) via Yarkovsky effect, could have produced the current
large dots show the locations of the 22 V-type asteroids that are not members of the family. Carruba et al.: On the V-type asteroids outside the Vesta family

Fig. 1. Location in proper element space (a-e, Fig. 1a, a-i, Fig. 1b) of the 5112 asteroids (small dots) members of the Vesta family (Mothè-Diniz et al. 2005). The asterisk shows the location of 4 Vesta itself, while the ellipse displays the 350 m/s level of maximum ejection velocity. The large dots show the locations of the 22 V-type asteroids that are not members of the family.

orbit of this asteroid. The role of close encounters with 4 Vesta may have been in this case to eject the asteroid from these resonances. We believe this mechanism could in principle apply to the case of five other asteroids close to these nonlinear secular resonances of node.

This article is so divided: in section 2 we discuss a new code that was developed to account for both Yarkovsky effect and close encounters with massive asteroids. In section 3 we show the results of a 500 Myr simulation of a fictitious Vesta family and estimated the maximum range of dynamical migration in $e$ and $i$ due to close encounters with massive asteroids, over 2 Gyr; in section 4 we study the case of a V-type asteroid, 2704 Julian Loewe, that could have migrated from the Vesta family via the interplay of Yarkovsky effect and two nonlinear secular resonances, and how close encounters with 4 Vesta could have helped in ejecting the asteroid out of these resonances. Finally, we present our conclusions.

2. Methods: effects of close encounters with 4 Vesta and the Yarkovsky effect

To investigate on the long-term relevance of close encounters and Yarkovsky effect we need a numerical tool able to simulate both effects. Until now, there were either codes able to simulate close encounters between a massive planet and massless particles (SWIFT-SKEEL, Levison and Duncan 2000) or codes to simulate the dynamical diffusion due to Yarkovsky effect (SWIFT-RMVSY, Brož 1999). In this work we created a new symplectic integrator, based on the Skeel-Biesiadescky development of the Hamiltonian (Biesiadecki and Skeel 1993), that also accounts for both the diurnal and seasonal version of the Yarkovsky effect.

To explain how this was done we need to discuss some characteristics of both SWIFT-SKEEL and SWIFT-RMVSY. SWIFT-SKEEL (SKEEL, hereafter) use mixed canonical variables, i.e., heliocentric coordinates and barycentric velocities. In these variables, the Hamiltonian can be split into two integrable parts and integrated by pieces. SKEEL subroutines consistently use heliocentric coordinates and barycentric velocities and accelerations.

SWIFT-RMVSY (RMVSY, hereafter) instead uses Jacobi canonical variables and splits the Hamiltonian in three parts. The equations corresponding to these parts can be rewritten into the heliocentric coordinates and velocities. The third part of the acceleration is evaluated by letting the coordinates drift along a straight line. RMVSY systematically uses heliocentric coordinates.

To compute the Yarkovsky acceleration in SKEEL we first converted the accelerations from the barycentric into the heliocentric frame. To explain how this was done we need to discuss some characteristics of both SWIFT-SKEEL and SWIFT-RMVSY. SWIFT-SKEEL (SKEEL, hereafter) use mixed canonical variables, i.e., heliocentric coordinates and barycentric velocities. In these variables, the Hamiltonian can be split into two integrable parts and integrated by pieces. SKEEL subroutines consistently use heliocentric coordinates and barycentric velocities and accelerations.

To test the new code we made several numerical integrations, using 25 test particles belonging to the Gefion family. We used the following thermal parameters: $\rho_{\text{bulk}} = 2500 \text{ kg/m}^3$, $\rho_{\text{surface}} = 1500 \text{ kg/m}^3$, $K = 0.001 \text{ W/m}^3$ $\text{K}$, $C = 680 \text{ J/Kg}$, $A = 0.1$, $\varepsilon = 0.9$. We used random orbital periods and we did not reorient our test particles during the integrations. We first integrated large asteroids (D $> 65$ km, Yarko-drift negligible) for 100 Myr with SKEEL and the new code (referred to as SP, hereafter). Then we integrated small asteroids (15 m) over 1 Myr with RMVSY and the new code. Finally we also included the three most massive asteroids. Figs. 2 show results of the simulations for a) the integration with SKEEL, b) the one with RMVSY, for 10 Myr and particles with diameters of 16 m, and no massive asteroids, c) the one with SP and large asteroids, and d) the one with the SP and the same Yarkovsky parameters of b).
If the new code works properly, differences between Figs. 2a and c should be minimal and due to the small yarkovsky drift, while differences between Figs. 2b and d should be small and due to the interaction of test particles with strong mean-motion resonances. We checked the behavior of all 25 particles in simulations Figs. 2b and d and, apart for a particle, that in the integration with RMVSY passed through the 5/2 resonance, while in the new code integration was captured, the rest of the simulated bodies show the same time-behavior.

To more accurately compare the results of different integrations, we computed the fractional change in orbital elements between one simulation and the other. For example, from the semimajor axis of a particle in the simulation with SKEEL and the new code (SP) of 65 km of diameter, we computed the quantity \( \frac{a_{\text{SKEEL}} - a_{\text{SP}}}{a_{\text{SKEEL}}} \) (and so forth for the other orbital elements). We then determined the mean and standard deviation of these percentual variations for all the simulated asteroids. To obtain an estimate of the numerical error of SKEEL, we compute the mean and standard deviation of the fractional change in orbital elements for the same 25 particles integrated with SKEEL twice over 100 Myr. We then computed the fractional changes between simulations a) and c) and b) and d). In all cases, the average values of fractional changes in orbital elements was less then the average value due to numerical errors, plus three standard deviations.

Based on these results, we believe the new code should be trustworthy. The final step was to compare the result of a simulation with the new code with and without massive asteroids. We did a simulation with asteroids of 2 km of diameters, with and without the three most massive asteroids in the main belt. Results show that the code is able to account for the effect of close encounters, as already shown in the previous simulations. Sudden variations in \( a, e, i \) due to close encounters with 4 Vesta and 1 Ceres are only observed when the massive asteroids are considered.
3. Close encounters with 4 Vesta: results

Now that we have a numerical tool to simulate both close encounters with 4 Vesta and Yarkovsky effect, we can try to apply it to the case of the Vesta family, to determine if close encounters with Vesta can generate a sufficient diffusion in proper $e$ and $i$ to explain the current population of V-type asteroids outside the family. To obtain better estimates of the rates of diffusion in $e$ and $i$ due to close encounters we generated a fictitious family and integrated it with the new code, under the action of the planets from Venus to Neptune, plus the three most massive asteroids (1 Ceres, 2 Pallas, and 4 Vesta).

We use the approach described in Carruba et al. 2002 to obtain the initial orbital distribution ($f_{KE} = 0.01$, where $f_{KE}$ is an unknown factor that takes into account that only a portion of the specific impact energy goes into the fragment’s kinetic energy). The sizes were chosen to simulate the size distribution of the V-type asteroids (they range from 6 km to 800 m). We used the following thermal parameters: $\rho_{\text{bulk}} = 3500 \text{ kg/m}^3$, $\rho_{\text{surface}} = 1500 \text{ kg/m}^3$, $K = 2.65 \text{ W/m}^2/\text{K}$, $C = 680 \text{ J/Kg/K}$, $A = 0.1$, and $\epsilon = 0.9$ (Farinella et al. 1998).

We estimate the $a$-evolution due to Yarkovsky over 1 Gyr, the maximum estimate for the family age (Marzari et al. 1996). We determined the radii of the 22 V-type objects by using their absolute magnitude $H$ and a value of the albedo of 0.25 (the average between the albedo of Magnya and Vesta). To estimate the drift in semimajor axis due to Yarkovsky effect we used the model of Vokrouhlický 1999. We consider maximum drift, i.e., no reorientations and $0^\circ$ obliquity, and the thermal parameters used for generating the fictitious family. Fig. 3 shows values of $da$ over 1 Gyr, while the bar size is proportional to the number of V-type asteroids in that size-bin. Fig. 3 can be used to estimate the maximum $a$-drift covered by the 22 V-type asteroids during 1 Gyr. Values of the drift obtained from our simulations are in agreement with the analytical estimates.

Variations in eccentricity and inclination due to Yarkovsky effect are negligible, but we may want to consider the evolution due to scattering by massive asteroids. We refer to results obtained for members of fictitious Vesta family, over 500 Myr. In Figs. 4 we show the initial and final distribution, in averaged $a - e$ elements, of the simulated test particles. From our results, we computed the time evolution of mean values of changes in $a$, $e$, and $i$ only due to close encounters for all simulated particle, and the corresponding standard deviations. This was done by computing the variations in $a, e$, and $i$ due to each close encounter with a massive asteroids for each particle, and by determining the average and standard deviation of these variations for all the simulated asteroids (Table 1).

We found a drift rate in $a$ of $(2 \pm 2.5) \times 10^{-3}$ AU/(100 Myr). While the large errors do not allow to make a conclusion, the average value is twice the drift rate found by Carruba et al. 2003 for members of the Gefion family. This may be due to the fact that we integrated test particles extremely close in phase space to 4 Vesta, with a high initial collision probability. As the particles
Fig. 4. Initial a) and final b) distribution in the proper $a$-$e$ space of the elements of the members of the fictitious Vesta family. The ellipse represents the line of 350 m/s of maximal initial ejection velocity.

Fig. 5. The black ellipse represent ellipses of maximal ejection velocity of 350 m/s in the $a$–$e$ and $a$–$i$ planes, while the green ellipse show the average distance that could have been covered due to close encounters with massive asteroids by an asteroid starting with an ejection velocity of 350 m/s, after 1 Gyr. Finally, the red ellipse refers to the mean value of changes plus a standard deviations (this refers to the $\approx 14\%$ of simulated objects that experienced the maximal observed change in proper elements due to close encounters).

diffused, we observed that the drift rates due to close encounters diminished as well. The values of drift rates we obtained are therefore to be intended as maximal estimates, and cannot be safely extrapolated beyond twice or three times the simulation timespan (500 Myr).

We then computed the maximum values of initial eccentricity, inclination, and semimajor axis around Vesta (black ellipse in the figures), for a value of ejection velocity of 350 m/s, and for a value of mean anomaly at break-up of the parent body of $75^\circ$, and of $M + \omega = 90^\circ$. To account for the dynamical evolution in proper element space we considered the mean drift in $a$, $e$, and $i$, due to close encounters with massive asteroids, and summed these values to the initial diffusion due to break-up (green ellipses, Figs. 5). The red ellipses refer to a drift equal to the mean changes plus one standard deviation. This distances was actually covered by $\approx 14\%$ of the simulated objects.

Our simulations show that close encounters alone could, in principle, be responsible of the current orbits of eight V-type asteroids outside the dynamical family: 2442, 2640, 2704, 2795, 2912, 4188, 4434, 4977). This corresponds to 36% of the currently known V-type asteroids in the inner belt, outside the family.
Fig. 6. Location in proper element space ($a-e$, Fig. 6a, $a-i$, Fig. 6b) of the 5112 asteroids (small dots) members of the Vesta family (Mothe-Diniz et al. 2005), in the region between $a = 2.35$ AU and $a = 2.46$ AU. The asterisk shows the location of 4 Vesta itself, while red dots show the orbital locations of the V-type asteroids. Large black dots display the V-type asteroids that are close to the $\sigma_6$ and $\sigma_7$ resonances.

4. The case of 2704 Julian Loewe

A limit of our previous results is that they are very qualitative. It is impossible to demonstrate that an asteroid had in the past a close encounter with 4 Vesta, due to the finite Lyapunov time of asteroidal orbits. Asteroid orbits in the Vesta region are chaotic on timescales of 100 Myr at most. Beyond this timescale, no significant dynamical information can be obtained.

However, close encounters may indeed have played an important role in causing the current orbital locations of V-type asteroids outside the Vesta family. A case that could be of interest is that of the five asteroids close to the $\sigma_6$ ($s-s_4+g_6-g_5$) and $\sigma_7$ ($s-s_4+g_6-g_7$) secular resonances. Figs. 6 show the locations in the $a-e$ and $a-i$ space of the five asteroids close to these resonances. While none of them is currently inside the two resonances (which, essentially, overlap, since the difference between $g_5$ and $g_7$ is of less than 1.2 “/yr), all of the five asteroids have circulation periods of the resonant argument longer than 4 Myr, and one, 2704 Julian Loewe, is extremely close to the two resonances. In this section we will investigate the hypothesis that asteroids from the Vesta family migrated via Yarkovsky effect into the $\sigma_6$ and $\sigma_7$ secular resonances, and were ejected from the resonances due to close encounters with 4 Vesta.

To investigate this hypothesis, we ...

5. Discussions

In this work we studied ...

Acknowledgements. Part of this work was supported by FAPESP (grant 03/07462-8) and CNPq.

References

Fig. 7. The plot shows the location of the $\sigma_6$ ($s_4 + g_6 - g_5$) and of the $\sigma_7$ ($s_4 + g_6 - g_7$) resonances (red circles), as found by plotting the resonant arguments of the test particles. The black full circle displays the actual position of 2704 Julian Loewe (osculating elements computed for October 21 2004, and referred to the invariable plane of the Solar System, and small dots show all the initial conditions used.

Table 1. Drift rates in proper $a, e, i$ due to close encounters with massive asteroids per Myr. We report the average value ($\pm$ one standard deviation) of the changes observed for the simulated Vesta family particles over the 500 Myr integration.

<table>
<thead>
<tr>
<th>$\Delta a$</th>
<th>$\Delta e$</th>
<th>$\Delta i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AU/Myr</td>
<td>1/Myr</td>
<td>degrees/Myr</td>
</tr>
<tr>
<td>$(2.0\pm2.5)\times10^{-5}$</td>
<td>$(2.0\pm2.3)\times10^{-5}$</td>
<td>$(6\pm5)\times10^{-4}$</td>
</tr>
</tbody>
</table>