Evolution of planet crossing asteroids in the inner Main Belt

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Abstract. We studied the dynamical evolution of asteroids in terrestrial planet crossing orbits, located between 2.1 and 2.5 AU. The evolution is analyzed by direct numerical integration of massless particles under the gravitational influence of all planets from Venus to Neptune. The simulations include the Yarkovsky effect, introduced as a non conservative force that produces a slow variation of the average orbital semimajor axis. Our analysis focuses on the test particles that can reach the middle and outer regions of the Main Belt (semimajor axis > 2.5 AU) during their evolution, since these may be relevant for understanding the transport mechanisms of asteroids from the inner Belt. These mechanisms could help to explain, for example, the existence of basaltic asteroids beyond 2.5 AU assuming that these bodies originate in the Vesta family, located at ∼ 2.3 AU. We found that, although some orbits that reach the middle and outer regions of the Belt can become temporarily detached from the planet crossing regime, and may have their orbital eccentricities damped due to capture at some mean motion resonances, such orbits survive for only a few hundred thousand years and, ultimately, the test particles return to the planet crossing regime being eventually discarded by close encounters with the planets. These results seem to indicate that a transport mechanism based only on planetary encounters and resonant capture might not be efficient enough to justify the presence of basaltic asteroids beyond 2.5 AU.

1. Introduction

One aspect of the dynamical evolution of small Solar System bodies that has called the attention of astronomers during the last decade, refers to the occurrence of mechanisms of dynamical transport that produce significant changes of the mean distances to the Sun. These mechanisms help to explain some phenomena observed in the Main Asteroid Belt, like the structure of asteroid families and the origin of small bodies populations as the Near-Earth Asteroids (NEAs).

The mechanisms responsible for these variations in orbital semimajor axis can be conservative or non conservative. Among the former, there is the gravitational swing-by effect that occurs when a small body approaches a planet and undergoes a significant change of its orbital energy and angular momentum relative to the Sun. Among the latter, there is the Yarkovsky effect which is a force caused by the thermal reemission at the surface of a small rotating body. These two effects could be combined with other dynamical processes, such as the chaotic evolution at mean motion and secular resonances, that favor the resonance capture through certain phenomena like the resonant stickiness.

Nesvorn et al. (2008) and Roig et al. (2008) presented results of numerical simulations showing that the variation of the semimajor axis due to the Yarkovsky effect and the interaction
with mean motion and secular resonances helps to explain the presence of basaltic asteroids in the inner Belt outside the Vesta family. We must recall that the only well established source of basaltic asteroids in the Main Belt is an impact crater excavated on the surface of asteroid 4 Vesta, and that some basaltic asteroids are located too far from Vesta as to be explained only such collisional impact. Nesvorn et al. (2008) analyze the evolution of real and cloned objects of the known Vesta family over a time interval of $2 \times 10^9$ years. Their results show that a large fraction of the original family members may have evolved beyond the borders of the family, reaching a final distribution compatible with the presently observed one. Moreover, Roig et al. (2008) show that Vesta family members with diameters smaller than 3 km, can cross the 3:1 mean motion resonance with Jupiter reaching stable orbits in the middle Belt ($a > 2.5 \text{AU}$).

A serendipitous result of the two works mentioned above was the identification of a dynamical path starting in the Vesta family and ending on a stable orbit in the middle Belt. This path is shown in Fig. 1 and involves four stages: i) inwards drift in semimajor axis due to the Yarkovsky orbital (red), ii) successive captures into some chaotic mean motion resonances, with the consequent increase of the orbital eccentricity (cyan), iii) capture into a planet crossing regime with Mars, and possibly also with the Earth (black), and vi) detach from the planet crossing regime due to resonance stickiness and temporary capture into the 8:3 mean motion resonance with Jupiter (magenta). Nevertheless, this behavior was observed in only 1 out of 6600 test orbits, which implies that it should be quite unlikely.

![Figure 1](image.png)

**Figure 1.** Evolutionary path of a test particle from the Vesta family (yellow dots) to the middle Main Belt. The different colors identify the different stages of the path. Left: eccentricity vs. semimajor axis. Right: inclination vs. semimajor axis. The plotted orbital parameters are averages over $10^6$ years.

The purpose of this work is to analyze in more detail some stages of this dynamical path, aiming for a better estimate of its occurrence probability and its actual efficiency for transporting asteroids from the inner Main Belt to beyond 2.5 AU. We focus particularly on the evolution of orbits that already entered the terrestrial planet crossing regime, and follow their paths into the middle and outer Belt. Along these stages, the evolution times are relatively short, of the order of $10^7$ years, which allows to perform a large number of numerical simulations at a low computational cost. Moreover, the analysis of these dynamical stages turns to be sufficient to address the efficiency of the whole transport mechanism from its initial stages.

In section 2 we introduce the applied methodology, and in section 3 we present our results. Section 4 is devoted to the conclusions.
2. Methodology
We studied the dynamical evolution of test particles through numerical integration of a Solar System model including perturbations of the planets from Venus to Neptune and a non conservative force mimicking the Yarkovsky effect. We considered orbits of real and fictitious asteroids initially crossing the orbit of Mars. The initial conditions for the planets and the real asteroids were obtained from the ephemeris of the Jet Propulsion Laboratory (JPL). The mass of Mercury was added to the mass of the Sun applying the corresponding barycentric correction, and the orbits were referred to the invariable plane of the Solar System.

The equations of motions were propagated using the symplectic scheme of Wisdom-Holman-Skeel, that consistently reduce the integration time step during close encounters. The time step was set to 0.03 years, and data output was recorded every $10^4$ years.

The test particles were removed from the simulation if: i) they had a close encounter with any planet at a distance less than 1% of the corresponding Hill’s sphere, ii) they reached a heliocentric distance larger than 10 AU, and iii) their heliocentric or pericentric distances were smaller than 0.01 AU.

Our simulations spanned a total time of $10^7$ years, consistent with the times of the dynamical stages we are analyzing. It is worth noting, however, that this time span is only 10% the typical lifetime of a Mars crosser asteroid ($\approx 110 \times 10^6$ years; Migliorini et al. 1998). Therefore, our results must be considered with caution and regarded only as a first approach to the dynamics of the problem.

![Figure 2. Distribution of the initial conditions of the sample Real3263 (blacks dots). Gray dots represent the asteroids in the inner Main Belt. Left: eccentricity vs. semimajor axis. Right: inclination vs. semimajor axis.](image)

We selected initial conditions of 3263 real Mars crossers with multi oppositional orbits between 2.1 and 2.4 AU. This sample was named Real3263 and is shown in Fig. 2. We furthermore generated three grids of 1000 fictitious initial conditions each, initially crossing the orbit of Mars. These orbits were randomly sorted from a uniform deviate within the ranges 2.1 to 2.4 AU in semimajor axis, $0^\circ$ to $19^\circ$ in inclination, and $0^\circ$ to $360^\circ$ in $\lambda$, $\varpi$ and $\Omega$. The eccentricities were set accordingly among three different intervals of perihelion distance: $1.33 < q < 1.44$ AU, $1.44 < q < 1.55$ AU, and $1.55 < q < 1.66$ AU. These samples were named $P_{P,1000}$, $P_{m,1000}$ and $P_{q,1000}$, respectively, and are shown in Fig. 3.

The evolution of each test particle was monitored until it eventually reached a semimajor axis $> 2.5$ AU. We assumed that a particle was effectively ”transported” beyond the inner Main Belt if it continuously remained with $a > 2.5$ AU for a time interval $\Delta T \geq 10^5$ years. It may
happen that a given particle was transported once by a given time interval $\Delta T_1$, then returned back to the inner belt ($a < 2.5$ AU), then it was transported again by another time interval $\Delta T_2$, and so on. In such case, we considered $\Delta T = \sum_i \Delta T_i$.

In order to qualitatively analyze the behavior of the transported particles, we also built maps of residence times. We subdivide the space of eccentricity vs. semimajor axis in $20 \times 70$ cells, each of $0.05 \times 0.01$ AU in size, within the limits $0 < e < 1$ and $2.5 < a < 3.2$ AU. Then, we determined the corresponding time interval that each orbit continuously remained in each cell during the simulation, and for each cell we computed average time interval over all the orbits. We thus obtained for each cell the factor $\Gamma$, which represents the (average) residence time of any particle in that cell.

3. Results

Figure 4(left) shows the number of surviving particles in the sample Real3263 as a function of time. The black curve represents the total population, while the blue and red curves represent the populations with initially "low" and "high" inclination orbits, respectively. As expected, the half-life of this sample of real Mars crossers is actually much larger than the time span of our simulation. The distinction between orbits with initially "low" and "high" inclination is an rough indicator of evolution outside and inside the $\nu_6$ secular resonance, respectively. It is worth recalling that the chaotic evolution in this secular resonance is responsible for the notorious depletion of real asteroids at high inclinations, as shown for example in Fig. 2.

Figure 4(right) shows the map of residence times beyond $2.5$ AU for all the particles of the sample. The thin stalactite shape observed around $2.9-3.0$ AU is related to temporary captures into resonance, possibly caused by resonant stickiness.

Figure 5(left) shows the distribution of the individual residence times, $\Delta T$, of the "transported" particles during the simulation the sample $P_g1000$. The residence times are very short, in most cases of the order of the imposed minimum ($10^5$ years), and only in a few cases the particles stayed a few million years. Figure 5(right) shows the corresponding map of residence times for the whole sample. Similar portraits are presented in Figs. 6 and 7 for samples $P_m1000$ and $P_p1000$, respectively.

A comparative analysis between these three samples indicates that the smaller the initial perihelion distance, the larger the residence time beyond $2.5$AU. But this is likely to be related to the larger number of transported particles for smaller initial perihelion distances. The maps
Figure 4. Results for the sample Real3263. Left: total number of surviving particles as a function of time (black curve), and the corresponding low (blue) and high (red) inclination populations. Right: map of residence times $\Gamma$.

of residence times show that the smaller the initial perihelia, the larger the area “visited” by the transported orbits. This favors the occurrence of temporary captures into resonances, as shown by the stalactite structures in Figs. 6 and 7.

Figure 5. Results for the sample $P_g 1000$. Left: distribution of $\Delta T$ for the “transported” particles. Right: map of residence times $\Gamma$.

Our results indicate that the larger the number of transported orbits beyond 2.5 AU, the greater the probability of having resonant captures Therefore, the results for the samples having lifetimes much longer than our simulation time span should be considered with caution, since they could change significantly if the simulations are extended over longer time spans.

4. Conclusions
We can conclude that, although some orbits in our simulations may reach the middle and outer regions of the Main Belt, becoming temporarily detached from the planet crossing regime and having their eccentricities damped due to captures into mean motion resonances (probably
through resonant stickiness), such orbital configurations only survive for time intervals up to $10^5$–$10^6$ years. These orbits eventually return back to the planet crossing regime, and the particles are discarded due to a close encounter with a planet.

These results seem to indicate that a transport mechanism similar to that shown in Fig. 1 might not be efficient enough to justify the presence of basaltic asteroids beyond 2.5 AU. We must note, however, that our simulations do not span sufficiently long times, and by extending them over longer intervals (e.g. $10^8$ years) we might get more favorable results.

References
[1] F. Migliorini, P. Michel, A. Morbidelli, D. Nesvorny, and V. Zappala. Origin of Multikilometer Earth- and Mars-Crossing Asteroids: A Quantitative Simulation. Science, 281:2022–+, Sept. 1998.
[2] D. Nesvorny, F. Roig, B. Gladman, D. Lazzaro, V. Carruba, and T. Mothé-Diniz, Fugitives from the Vesta family, Icarus 193 (2008), 85–95.
[3] F. Roig, D. Nesvorny, R. Gil-Hutton, and D. Lazzaro, V-type asteroids in the middle main belt, Icarus 194 (2008), 125–136.