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Some of the most interesting cases of close asteroid pairs perturbed by resonance

A. Rosaev[1] **and Eva Plavalova**[2]

[1]Research and Educational Center "Nonlinear Dynamics",
Yaroslavl State University, Yaroslavl, Russia,
email: hegem@mail.ru

[2]Mathemailcal institute, Slovak academy of Science,
Bratislava, Slovakia
email: plavalova@mat.savba.sk, plavalova@komplet.sk

Abstract. We have randomly selected 20 close asteroid pairs (younger than 800 kyr) from known pairs, and by the application of backward numerical integration we have calculated their orbits. For the reason of speeding up the process of making the resonances visible, we have used a high value of Yarkowsky drift. The results of the calculation show that only two pairs appear to have a simple resonance with Earth and Jupiter while half of the tested pairs are visibly in the vicinity of three-body resonances.

We have found a 2-1J-1M resonance for the pair (56232) 1999 JM_{31} and (115978) 2003 WQ_{56}. Following our study of the pair (10123) Fideoja and (117306) 2004 VF_{21}, we discovered a different resonance than the 7-2J mean motion resonance previously published: we have proved that this pair is perturbed by 9-6J-4M three body resonance.

Keywords. asteroid pairs, orbital evolutions, resonance

1. Introduction

Asteroids tend to group into so-called families or into associations of objects sharing similar orbits. Most of them are the results of very old (about 1 Gyrs) collisions between asteroids (Spoto et al. 2015; Nesvorny et al. 2015). Since the beginning of the twentieth century, asteroid families and pairs have been the object of increasingly intensive studies.

The detection of several asteroid families and pairs with very recent formations (about 1.5 Myr or less) in the past decades has generated a new and exciting development. These discoveries are very important, because various collisional and dynamical processes have had little time to act on these families to alter their properties. Recent studies have shown that some asteroid families can also be the outcomes - in theist; however of a spin-up-induced fission of a critically rotating parent body (fission clusters, Jacobson and Scheeres 2011). Moreover, cases of subsequent breakups can take place in older families (Fatka et al. 2020).

It is important to note that the age of a young family can be determined by numerically integrating the orbits of its members backward in time and demonstrating that they converge to each other at some specific time in the past, however, the method of backward integration of orbits only works for families younger than a few million years.

Many cases of the resonance perturbations of young families and pairs are known. A prime example is the Datura family with its 9-16M resonance with Mars (Nesvorny et al. 2006). The chaotic orbits of the pair (49791) 1999 XF_{31} and (436459) 2011 CL_{97} may be explained by the 15-8M mean motion resonance with Mars (Pravec et al. 2018) and the pair (7343) Ockeghem and (154634) 2003 XX_{38} is in the 2-1J-1M three-body resonance (Duddy et al. 2012).

The main goal of this paper is to search for very young asteroid pairs (younger than 1 Myr) within the influence of resonances. We identify the types of resonances, their position and their chaotic zone.

2. Methods

To study the dynamic evolution of asteroid pairs, the equations of the motion of the systems were numerically integrated over 800 kyr using the N-body integrator Mercury (Chambers 1999) and the Everhart integration method (Everhart 1985).

Under the condition of finding two- or three- body mean motion resonances up to the order of 20, we tested 20 pairs of asteroids (Tab. 1), arbitrarily selected from Pravec et al. (2018). To calculate the nominal resonance positions, we used the values of the time-averaged planet semi-major axes: 1.52368 AU for Mars, 5.20259 AU for Jupiter and 9.5549 AU for Saturn. For the reason of speeding up the process of making the resonances visible, we set a very large value of Yarkovsky drift, applying non-gravitational force parameters for the asteroids $A_2 = 1 \cdot 10^{-13}$ and adapting numerical integrations with different planetary perturbations. The Yarkovsky effect is usually characterized by value da/dt; this parameter is directly proportional to value A_2 used in our integrations (see for example Farnocchia et al. 2013)

3. Results

Only one of the studied pairs, namely 21436 Chaoyichi and (334916) 2003 YK_{39} is close to the simple two-body mean motion resonance 11-3J with Jupiter and the pair (5026) Martes and 2005 WW_{113} is close to the simple two-body mean motion resonance 3-11E with Earth. However, for more than half of the studied pairs, we detect three-body resonances in distances less than d=0.0006 AU for at least one of the asteroids of the pair (Tab. 1). Asteroid-Jupiter-Saturn resonance was found in only five of the studied pairs (see Tab. 1) and all the other resonance cases include planets of the Earth group; asteroid-Earth (or Mars)-Jupiter. This fact highlights the role of Earth group planets on the dynamics of the inner asteroid belt.

The second half of the asteroid pair orbits we studied lie more distant from any resonance ($d > 0.0006$ AU) and have no notable perturbations. At this condition there are not any periodic variations of semi-major axis with large amplitudes and not any jumps. Therefore, this value of the distance of resonances may be considered as a rough boundary since which resonance perturbations are insignificant.

Such a high percentage of resonance-perturbed asteroid pairs allows us to suppose that the resonances play a significant role in the process of pair formation. In light of this relation, new theoretical researches on the process of the origin of asteroid pairs are required. Below we report about some of the most interesting cases we studied.

4. Two asteroid pairs in 2-1J-1M resonance

Pravec et al. (2018) estimated a lower limit of 382 kyr for the age of the pair (7343) Ockeghem and (154634) 2003 XX_{38}. Duddy et al. (2012) found that these two asteroids have very similar spectra to that of S class. They identified that this pair was orbiting in the 2-1J-1M three body resonance. The resonance argument is:

$$\varphi = 2\lambda - \lambda_{Jupiter} - \lambda_{Mars} \tag{4.1}$$

Here $\lambda, \lambda_{Jupiter}, \lambda_{Mars}$ are the longitudes of the asteroid, Jupiter and Mars accordingly.

We conducted backward integrations on the orbit of this pair with different values of the Yarkovsky effect. We observe that in the case of medium values of the coefficient

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Table 1. Selected close young asteroid pairs and their resonances.

Pair	Proper a [AU]	Resonance	a_r [AU]
(4765) Wasserburg (350716) 2001 XO_{105}	1.94542 1.94563	5-10J-1E	1.945479
(404118) 2013 AF_{40} (355258) 2007 LY_4	2.21744 2.21746	2+10J-7S	2.217453
(44620) 1999 RS_{43} (295745) 2008 UH_{98}	2.17644 2.17669	2+9J-4S	2.176198
(80218) 1999 VO_{123} (213471) 2002 ES_{90}	2.2185 2.21864	1+6J-6S	2.219288
(7343) Ockeghem (154634) 2003 XX_{38}	2.19254 2.19253	2-1J-1M	2.192728
(56232) 1999 JM_{31} (115978) 2003 WQ_{56}	2.19332 2.19328	2-1J-1M	2.192728
(26420) 1999 XL_{103} 2012 TS_{209}	2.19757 2.19749	6-10J-1E	2.196919
(2110) Moore-Sitterly (44612) 1999 RP_{27}	2.19804 2.19787	no	
(8306) Shoko 2011 SR_{158}	2.24159 2.24125	3-9J -4S	2.241658
(10123) Fideoja (117306) 2004 VF_{21}	2.26964 2.26962	9-6J-4M	2.269495
(17198) Gorjup (229056) 2004 FC_{126})	2.27969 2.27962	no	
(6369) 1983 UC (510132) 2010 UY_{57}	2.29324 2.29315	7-5J-3M	2.292687
(49791) 1999 XF_{31} (436459) 2011 CL_{97}	2.31665 2.31663	8-8J-3M	2.316370
(25021) Nischaykumar (453818) 2011 SJ_{109}	2.31788 2.31779	no	
(26416) 1999 XM_{84} (214954) 2007 WO_{58}	2.34257 2.34256	no	
(43008) 1999 UD_{31} (441549) 2008 TM_{68}	2.3481 2.34773	2+7J-1S	2.347592
(5026) Martes 2005 WW113	2.37752 2.37752	3-11E	2.377825
(46829)McMahon 2014 VR_4	2.39991 2.40048	no	
(42946) 1999 TU_{95} (165548) 2001 DO_{37}	2.56782 2.56761	no	
(4905) Hiromi (7813) Anderserikson	2.60102 2.60112	no	

Yarkovsky drift in semi-major axis $A_2 = 1 \cdot 10^{-14}$, asteroids stay within the neighbourhood of resonance in a stable orbit for at least 1 Myr. Conversely, when a larger value is used i.e. $A_2 = 1 \cdot 10^{-13}$, we observe a jump from one side of resonance to the other (Fig. 1). Both members of this pair are trapped in the considered resonance.

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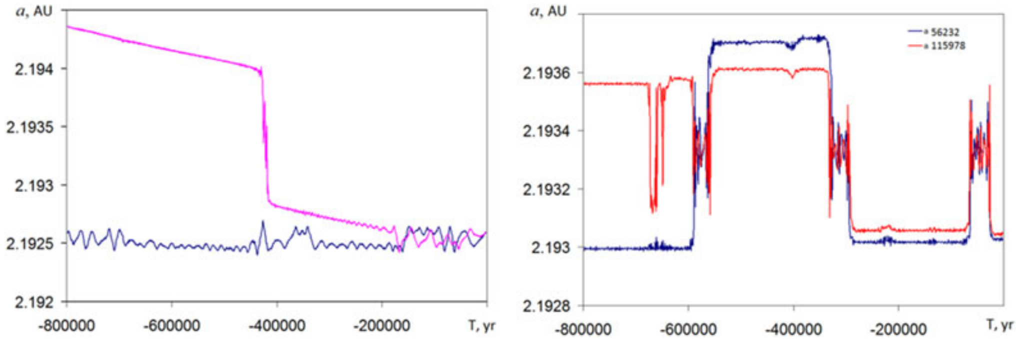

Figure 1. The left figure shows the evolution of the semi-major axes of the pair (7343) Ockeghem and (154634) 2003 XX_{38} - (Yarkovsky effect is set at $A_2 = \pm 10^{-13}$). The right figure shows the evolution of semi-major axes of pair 56232 (1999) JM_{31} and (115978) 2003 WQ_{56} (Yarkovsky effect is NOT accounted for).

We calculate that the observed centre of the chaotic resonance zone is a=2.19340 AU (Fig. 1, left figure). The nominal position of this resonance is 2.192728 AU.

We have found a second pair (56232) 1999 JM_{31} and (115978) 2003 WQ_{56} close to the same resonance (Fig. 1, right figure). Backward integration of their heliocentric orbits suggest that these two asteroids separated about 130 kyr ago (Pravec et al. 2018). The proper elements of both pairs are very similar and therefore the resonance 2-1J-1M has a significant effect on both pairs.

However, using backward integration with the Yarkovsky effect taken into account, we have found that the position of the centre of resonance for the second pair is different, at about a=2.19333 AU. Although the difference is small, it still requires an explanation.

In our previous paper Rosaev and Plavalova (2021) we have presented the approximation of orbital elements of some asteroids. Here we have applied this method to the considered pairs. The period of the (7343) Ockeghem perihelion precession is about 45.95 kyr. The detected period of short periodic eccentricity perturbation is about 46.06 kyr. The period of the 56232 (1999 JM_{31}) perihelion precession is about 45.49 kyr. The according period of short periodic eccentricity perturbation is about 45.40 kyr.

The long period in eccentricity is about 305.01 kyr for the (7343) Ockeghem - (154634) 2003 XX_{38} pair and 294.98 kyr for the (56232) 1999 JM31 - (115978) 2003 WQ56 pair.

The formal results of our eccentricity approximation for these two pairs using the method stated by Rosaev and Plavalova (2021) are:

$$e_{7343} = 0.15 + 0.054\cos(0.0206t + 2.3) - 0.025\cos(0.136t + 3.7) \tag{4.2}$$

$$e_{56232} = 0.15 + 0.049\cos(0.0213t + 0.2) - 0.024\cos(0.138t + 2.4) \tag{4.3}$$

We have highlighted the remarkable phase difference in eccentricity perturbations of these pairs (Fig. 2).

5. (10123) Fideoja and (117306) 2004 VF_{21} pair

Pravec et al. (2018) conducted backward numerical integrations of these two asteroids using a modest number of clones - that the pair orbits and revealing encounters about 1-2 Myr ago. They found that the primary (10123) Fideoja is a binary system while the satellite has a secondary-to-primary mean diameter ratio D1,s/D1,p =0.36±0.02 and an orbital period of 56.46 ±0.02 h. They note that the pair‘s orbits undergo irregular jumps over a 7-2J mean motion resonance with Jupiter.

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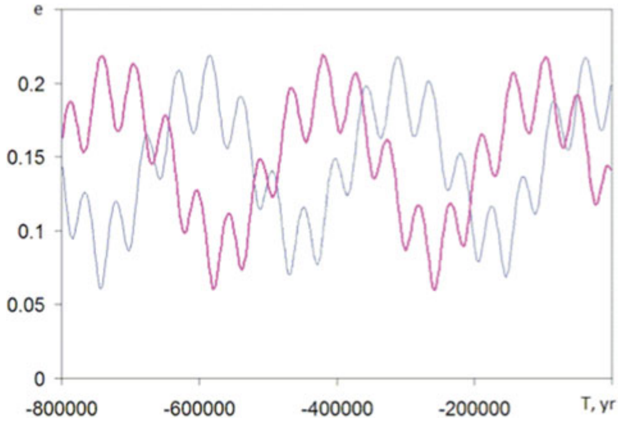

Figure 2. The nominal orbital evolution of eccentricity of (7343) Ockeghem (bold magenta line) and (56232) 1999 JM_{31} (thin gray line).

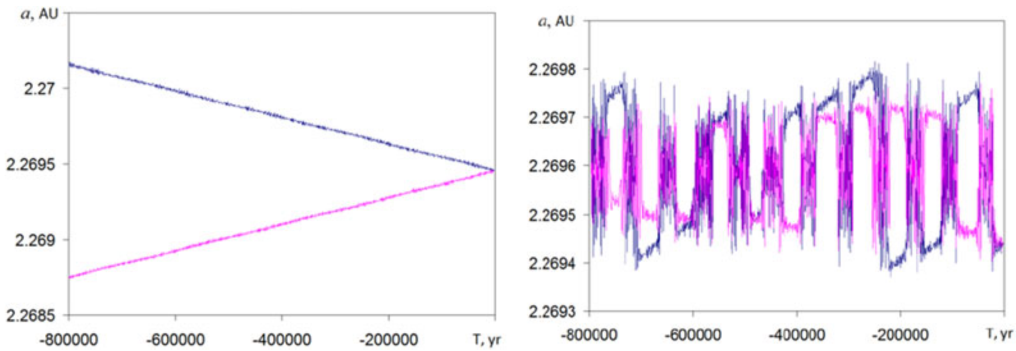

Figure 3. The left figure shows the evolution of the semi-major axis of pair Fideoja and (117306) 2004 VF_{21} for only Jupiter-Saturn-Earth perturbations. The right figure shows the evolution of the semi-major axis of the same pair for only Jupiter-Saturn-Mars perturbations.

We integrated the nominal orbits of this pair taking into account all large planetary perturbations. We obtained strong synchronous variations of the semi-major axis of both members as clear evidence of resonance perturbations. We determined the centre of the resonance related chaotic zone to be about 2.26960 ± 0.00001 AU. However, our study of the dynamics of this pair shows that they are not in 7-2J resonance, the nominal position of which would be about 2.2569 AU (i.e a difference of 0.011 AU).

In the search for resonance, we set a very large value of Yarkovsky drift ($A_2 = 1 \cdot 10^{-13}$) and applied numerical integrations with only one perturbing planet - Jupiter, or Earth, or Mars. These three calculations did not provide us with any resonance perturbations. We then repeated the integrations with perturbations from Jupiter-Saturn-Earth (Fig. 3 left) and Jupiter-Saturn-Mars (Fig. 3 right). As a result, we obtained clear evidence that the observed jumps in the semi-major axis of (10123) Fideoja and (117306) 2004 VF_{21} were caused by the three body resonance asteroid-Jupiter-Mars (9-6J-4M). Moreover, according to our numerical integration, the width of the chaotic zone related to the resonance is about 0.0003 AU. In this case the resonance argument has the form:

$$\varphi = 9\lambda - 6\lambda_{Jupiter} - 4\lambda_{Mars} \tag{5.1}$$

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6. Conclusions

We have focused on possible resonances for 20 randomly selected close young asteroid pairs (younger than 800 kyr). In order to find possible resonances, we have applied backward numerical integration using a very high value of Yarkovsky drift (using the non-gravitational force parameter for asteroids $A_2 = 1 \cdot 10^{-13}$).

Our findings reveal that half of the tested pairs are affected by three-body resonances within a distance less than 0.0006 AU. We deduce from this that asteroid-Earth-Jupiter and asteroid-Mars-Jupiter resonances are very important in the dynamics of close asteroid pairs in the inner and middle asteroid belt.

Here we have considered three most interesting cases: the pair (10123) Fideoja and (117306) 2004 VF_{21}, the pair (56232) 1999 JM_{31} and (115978) 2003 WQ_{56} and the pair (7343) Ockeghem and (154634) 2003 XX_{38} in details. We conclude that resonance perturbations may play an important role in the dynamical evolution of very young asteroid families and close pairs. It is necessary to account for this fact in the models of their origin and dynamical evolution.

In closing, compact asteroid families and pairs near resonance provide a unique opportunity to study in detail the resonance perturbations and the dynamical interaction of minor bodies with resonances.

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