Behavior of Jupiter Non-Trojan Co-Orbitals

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ABSTRACT

Searching for the non-Trojan Jupiter co-orbitals we have numerically integrated orbits of 3,160 asteroids and 24 comets discovered by October 2010 and situated within and close to the planet co-orbital region. Using this sample we have been able to select eight asteroids and three comets and have analyzed their orbital behavior in detail. Among them we have identified five new Jupiter co-orbitals: (241944) 2002 CU\textsuperscript{147}, 2006 SA\textsuperscript{387}, 2006 QL\textsuperscript{39}, 2007 GH\textsuperscript{6}, and 200P/Larsen, as well as we have identified six previously identified co-orbitals: (118624) 2000 HR\textsuperscript{24}, 2006 UG\textsuperscript{185}, 2001 QQ\textsuperscript{199}, 2004 AE\textsuperscript{9}, P/2003 WC\textsuperscript{7} LINEAR-CATALINA and P/2002 AR\textsuperscript{2} LINEAR.

(241944) 2002 CU\textsuperscript{147} is currently on a quasi-satellite orbit with repeatable transitions into the tadpole state. Similar behavior shows 2007 GH\textsuperscript{6} which additionally librates in a compound tadpole-quasi-satellite orbit. 2006 QL\textsuperscript{39} and 200P/Larsen are the co-orbitals of Jupiter which are temporarily moving in a horseshoe orbit occasionally interrupted by quasi-satellite behavior. 2006 SA\textsuperscript{387} is moving in a pure horseshoe orbit. Orbits of the latter three objects are unstable and according to our calculations, these objects will leave the horseshoe state in a few hundred years. Two asteroids, 2001 QQ\textsuperscript{199} and 2004 AE\textsuperscript{9}, are long-lived quasi-satellites of Jupiter. They will remain in this state for a few thousand years at least. The comets P/2002 AR\textsubscript{2} LINEAR and P/2003 WC\textsuperscript{7} LINEAR-CATALINA are also quasi-satellites of Jupiter. However, the non-gravitational effects may be significant in the motion of these comets. We have shown that P/2003 WC\textsuperscript{7} is moving in a quasi-satellite orbit and will stay in this regime to at least 2500 year. Asteroid (118624) 2000 HR\textsuperscript{24} will be temporarily captured in a quasi-satellite orbit near 2050 and we have identified another one object which shows similar behavior - the asteroid 2006 UG\textsuperscript{185}, although, its guiding center encloses the origin, it is not a quasi-satellite. The orbits of these two objects can be accurately calculated for a few hundred years forward and backward.

Key words: Minor planets, asteroids: general - Comets: general - Celestial mechanics - Methods: numerical

1. Introduction

Small bodies locked in a co-orbital region are usually associated with the Lagrangian equilibrium points. For more than one century the Lagrange points were only a subject of theoretical considerations. The first object, Trojan asteroid (588)
Achilles, that traces tadpole-shaped trajectory (TP) around Jupiter L₄ lagrangian point was discovered by Max Wolf in 1906. Trojan asteroids have also been discovered for Mars (Connors et al. 2005) and Neptune (Sheppard and Trujillo 2006).

Shortly after the discovery of the first Trojan, Brown (1911) indicated, that stable horseshoe (HS) orbits, that surround L₄, L₅ and L₃ Lagrangian points can exist. Another kind of 1:1 resonant trajectories, not associated with the Lagrangian points, recently known as quasi-satellite (QS) orbits (Lidov and Vashkov’yak 1994, Mikkola and Innanen 1997), were predicted by Jackson (1913).

All these families of orbits can be simply classified through the librational properties of the principal resonant angle, \( \sigma \), which is defined by \( \sigma = \lambda - \lambda_p \), where \( \lambda \) and \( \lambda_p \) are the mean longitude of the object and the planet respectively. TP orbits librate around ±60°, but for eccentric TP orbits their libration centers are displaced with respect to the equilateral locations at ±60° (Namouni and Murray 2000). HS orbits librate around 180° whereas QS librate around 0°.

In the planar case, the families of TP, HS and QS orbits are disjoint, however, in a case of sufficiently inclined and eccentric orbits there can exist compound orbits which are unions of the HS (or TP) and QS orbits, and transient co-orbital orbits for which transitions between different families occur (Namouni 1999, Namouni et al. 1999, Christou 2000, Brasser et al. 2004a, Wajer 2009, 2010). This type of resonant behavior has been observed in the motion of several known near-Earth asteroids.

We searched numerically for objects which are, or will be in the near future (in the next 100 years), co-orbitals of Jupiter and experience transitions between different types of co-orbital motion. We have selected these objects which have astrometric data collected over a longer period than 1 year and we have identified among them seven asteroids and one comet. Additionally, we decided to investigate three more objects of a shorter interval of observations (asteroid 2004 AE₉ and two comets: P/2002 AR₂ LINEAR and P/2003 WC₇ LINEAR-CATALINA which were previously investigated by Kinoshita and Nakai (2007).

2. Selection of objects and the method of numerical integration

The aim of this study was to find and analyze transient, compound co-orbitals or quasi-satellites of Jupiter. Therefore, we looked for objects located in the co-orbital area associated with this planet, i.e. those objects which orbital semimajor axis, \( a \), satisfies the following condition:

\[-\varepsilon \leq \Delta a = a_J - a \leq +\varepsilon,\]

where \( \varepsilon \approx 0.35528 \) a.u. is the Jupiter’s Hill radius and \( a_J \) – semi-major axis of Jupiter orbit.

According to this criterion we primarily selected 3160 asteroids discovered by October 2010, including 1213 numbered and 1947 unnumbered objects, respec-
tively taken from the AstDys pages\footnote{http://hamilton.dm.unipi.it/astdys/}, and 24 comets from the latest version of the “Catalogue of Cometary Orbits” (Marsden and Williams 2008), 11 observed only in one apparition, and 13 numbered short-period comets. To exclude an abundant population of Trojan asteroids from a pre-selected sample, we looked for objects that during the next thousand years (in the period between 2010 – 3010) do not librate all the time around one of the triangular Lagrange points, L4 or L5. In other words, they are not Trojans all the time, but at least temporary move in HS, TP or QS within the next 100 years, where the transitions are possible between all these types of orbits as well as compound orbits are included. Of the 3 160 pre-selected objects we have found seven new potentially interesting objects: (241944) 2002 CU\textsubscript{147}, 2006 SA\textsubscript{387}, 2006 QL\textsubscript{39}, 2007 GH\textsubscript{6}, (32511) 2001 NX\textsubscript{17}, 2006 SV\textsubscript{301} and 200P/Larsen, as well as six previously identified objects: (118624) 2000 HR\textsubscript{24}, 2006 UG\textsubscript{185}, 2001 QQ\textsubscript{199}, 2004 AE\textsubscript{9}, P/2003 WC\textsubscript{7} LINEAR-CATALINA and P/2002 AR\textsubscript{2} LINEAR. The dynamical behavior of seven objects is analyzed in detail in this paper. The reason why we decided not to include the two objects 2001 NX\textsubscript{17} and 2006 SV\textsubscript{301} is following. The first of them, 2001 NX\textsubscript{17}, is not captured into 1:1 mean motion resonance with Jupiter up to 2700, however, after this time about 11\% of VOs start to librate around L\textsubscript{5} point. The second, 2006 SV\textsubscript{301}, will be librate around L\textsubscript{5} for at least 1000 years and probably leave this state after the year 3000 (about 80\% of VOs show this behavior).

In addition, we expanded the asteroid search to objects whose semi-major axes satisfy the condition $\varepsilon < |\Delta a| \leq 2\varepsilon$, since co-orbital objects may have temporarily increased value of $|\Delta a|$, as in the case of 2003 YN\textsubscript{107} which was temporarily captured into the 1:1 resonance with the Earth (Connors et al. 2004). We have found 10 such asteroids (three numbered: 944, 6144 and 145485, and seven unnumbered objects: 2000 EJ\textsubscript{37}, 2005 TS\textsubscript{100}, 2006 UG\textsubscript{185}, 2008 UD\textsubscript{253}, 2000 AU\textsubscript{242}, 2002 AO\textsubscript{148}, 2010 AN\textsubscript{39}). None of these objects is librating in the Jupiter co-orbital region at present, but 2006 UG\textsubscript{185} will be temporarily captured into 1:1 mean motion resonance with Jupiter in the future. Thus, we have decided to include 2006 UG\textsubscript{185} to our study.

It is well-known that the non-gravitational effects (hereafter NG effects) play an important role in the motion of comets. They are important in determining the osculating orbits from observations even in a very short time scales, for short-period comets sometimes involving only two consecutive apparitions. Therefore, we have limited our analysis primarily to large perihelion distance comets ($q > 3$ a.u.). Using Eq. 1 we selected sample of 24 comets where 13 have observational interval longer than 1 yr. In this sample of 24 comets we had only four objects with $q > 3$ a.u.: 186P/Garradd, 200P/Larsen, 244P/Scotti (= 2000 Y\textsubscript{3}, 2010 Q\textsubscript{1}) and 2004 FY\textsubscript{140}. Of these four only 200P/Larsen moves in a dynamically interesting trajectory. However, we decided to include to our analysis also two comets discussed by Kinoshita and Nakai (2007), both with significantly smaller perihelion
distances than 3.0 a.u. and shorter interval od data than 1 yr. Thus, we were able to compare their results (based on a pure gravitational calculations) with our own analysis based on observational material from the same periods of time (the two comets were not observed after 2005) and pure gravitational calculations (NG effects for these two comets are indeterminable, see below).

Finally, we have taken a detailed analysis of the eight asteroids and three comets, where two of comets are only for comparison with Kinoshita and Nakai (2007). For each object from this sample we determined its osculating orbit (hereafter nominal orbit) based on the available observational material taken from IAU Minor Planet Center[3]. To derive the nominal orbit we used the least square orbit determination method where the equation of object’s motion have been integrated numerically using the recurrent power series method (Sitariski 1989, 2002). In the case of comets C/2002 AR₄, C/2003 WC₃ and 200P/Larsen we try to determine the NG effects using the standard-model expressions for outgassing acceleration acting on the comet in the radial (Sun-Comet) direction, transverse and normal direction (for more details see Marsden et al. 1973 and Yeomans et al. 2004).

Orbital elements (nominal orbit), together with the characteristics of observational material used for their determination are given in Table 1.

An analysis of the uncertainties of orbital elements given in Table 1 shows that four asteroids (two numbered, (241944) 2002 CU₁₄₇, (118624) 2000 HR₂₄, and two unnumbered, 2001 QQ₁₉₉, 2006 Q₇₃₉) and comet 200P/Larsen have orbits very well determined; the worst determined is the orbit of comet C/2002 AR₂ taken

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2http://www.minorplanetcenter.org/iau/ECS/MPCOBS/MPCOBS.html
only to compare with the result of Kinoshita and Nakai (2007).

In the case of comets, we realize that the only osculating orbit of the comet 200P/Larsen is based on the data taken from a sufficiently long time interval to draw conclusions about its dynamical evolution both because of their orbital uncertainties as well as large perihelion distance, which suggests that the NG effects less affect pure gravitational motion of this comet than in the case of the remaining two comets.

Comets C/2002 AR$_2$ and C/2003 WC$_7$ have perihelia at 2.1 a.u. and 1.7 a.u. from the Sun, respectively. Thus, the NG effects may be significant in the motion of these comets. Unfortunately, the short time intervals of astrometric observations (less than half a year) do not allow us to determine their NG orbits. Thus, these two comets have placed in the Table 1 after Kinoshita and Nakai (2007), only as a potentially interesting objects.

Although the comet 200P/Larsen has a perihelion farther from the Sun than those two (at 3.3 a.u. from the Sun), the NG effects are determinable by a much longer time interval of observations (more than 11 years). However, we calculated that taking into account the NG effects does not cause a significant decrease of RMS (only $\sim 0'0.4$; from $0'64$ to $0'60$). Nevertheless, comparing the pure gravitational dynamical evolution starting from the NG osculating orbit with that starting from the purely gravitational osculating orbit it seems obvious that we know very well the dynamical evolution of this comet only 94 years back (after the comet encounter with Jupiter in 1917) and for 230 years forward (to Jupiter close encounter in the year 2242). Therefore, the detailed discussion of the dynamical evolution of this comet (section 3.2) is constrained just to that period.

To examine the past and future dynamical evolution of investigated objects two hundred of virtual object (VO) orbits using the Sitarski’s method of the random orbit selection (Sitarski, 1998) were examined. The derived swarm of fictitious objects (VOs) follows the normal distribution in the space of orbital elements. Also the RMS’s fulfil the 6-dimensional normal statistics (thus, all VOs are compatible with observations; for more details see also Królikowska et al. 2009). Thus, as the starting data for our dynamical calculations we constructed (for each investigated object) osculating swarms of 201 VO orbits (including nominal orbit presented in Table 1).

The numerical orbit computations of the individual VO motion were performed using the recurrent power series (RPS) method (Hadjifotinou and Gousidou-Koutita 1998) by taking the perturbations by all eight planets, the Moon and Pluto into account (similarly as was taken for the osculating orbit determination). The RPS algorithm allows to determine the optimal value of the integration steps at each point along the orbit, ensuring the desired accuracy of results of computations is obtained. This method also give very good results in the case of close approaches of an object to the Sun and the planets (Sitarski 1979).

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3 Plut was included to obtain compatibility with the ephemeris DE406.
The objects and their VO's were treated as massless test particles. Since we focused mainly on the future dynamical evolution of the objects, the maximum integration length was 2000 Julian years backward only and 10000 years forward. The time interval of our integrations depends on the predictability time (i.e., qualitatively speaking, within the period where all VO's show very similar behavior) and was selected from a practical point of view (see section 3 as well as table 2 for the integration time).

3. Analysis of the results

3.1. Transient quasi-satellite-tadpole types of orbits: asteroids (241944) 2002 CU\textsubscript{147} and 2007 GH\textsubscript{6}

The asteroid (241944) 2002 CU\textsubscript{147} is currently not classified but the value of its Tisserand parameter with respect to Jupiter, $T_J = 2.60$\textsuperscript{4} suggests that it is asteroids in cometary orbits (ACO), see Sect. 4 for definition and discussions. This asteroid is currently a QS of Jupiter for about 200 years and will be in this state up to 2030 (Fig. 1, left panels). In this state the object is moving deep inside the co-orbital region ($|\Delta a| < 0.1e$) with amplitude of the principal resonant angle $\sigma \simeq 4^\circ$. Near 2030, the transition from QS to TP (libration around L\textsubscript{4} point) motion occurs. This TP phase lasts about 350 years and after 2650 the asteroid switches to librate around L\textsubscript{5} Lagrange point.

Figure 1 (left figures, top and middle panels) shows that as far as the past and future dynamical evolution of (241944) 2002 CU\textsubscript{147} is concerned, i.e. within the time interval [1000-7000], its motion undergoes transitions between two types of trajectories, QS and TP regimes, where (in TP type of motion) the guiding center of the asteroid librates either around L\textsubscript{4} or L\textsubscript{5} Lagrangian points. In the QS phases the asteroid’s change of semimajor axis is of order $|\Delta a| < 0.1e$, and the amplitude of libration of $\sigma$ is smaller than 12\textdegree. On the other hand, in the TP regimes, one has $|\Delta a| < 0.5e$ and the amplitude of libration of $\sigma$ is about 50\textdegree. At present the eccentricity and the inclination of the 2002 CU\textsubscript{147} is about 0.31 and 33\textdegree, respectively. The eccentricity changes between 0.11 and 0.37, the inclination - from about 30\textdegree to 36\textdegree.

Our calculations show that all VO's of (241944) 2002 CU\textsubscript{147} move on similar orbit up to about 6500, after that time they still move inside the co-orbital region of

\footnotesize\textsuperscript{4}which is defined by $T_J = a/a_J + 2\sqrt{(a/a_J)(1-e^2)}\cos I$, where $a$ and $a_J$ are the semimajor axis of the object and Jupiter, respectively, $e$ is the eccentricity, and $I$ is inclination relative to the orbital plane of Jupiter of the object’s. At the moment of proof correction this asteroid is classified as Main Belt Asteroid as the IAU Minor Planet Center Web page.

\footnotesize\textsuperscript{5}The motion of an asteroid in a co-orbital region is a superposition of two components: a short period three-dimensional epicyclic motion with amplitudes of $\sim ae$ and $\sim asini$, and a long period term corresponding to the averaged position of the asteroid with respect to the planet known as the guiding center of the motion. The motion of the guiding center is represented by the variables $\Delta a$ and $\sigma$ (Namouni et al. 1999, Christou 2000).
Figure 1: Asteroids (241944) 2002 CU₁₄⁷ (left) and 2007 GH₆ (right). Top: evolution of the guiding center of the asteroid. The time interval is the same as in the case of both middle and bottom panels, middle: evolution of the principal resonant angle of the representative subsample of 10 VOs (nominal orbit plus 9 randomly selected VOs), bottom: evolution of the semimajor axis of 10 VOs. The dashed line indicates the semimajor axis of Jupiter.
Jupiter but they show different behavior (Fig. 1 left figures, middle and bottom panels). We obtained that 14% of the VOs will continue the motion around L₅ point (starting from the year 3750), the remaining 86% will transit into orbits which librate around L₄ point. During the predictability time interval, the asteroid does not experience close approaches with Mars, Jupiter and Saturn. The smallest distances between each of these planets and (241944) 2002 CU₁₄₇ are over 1.80 a.u., 1.25 a.u. and 2.18 a.u., respectively.

The asteroid 2007 GH₆ is currently moving on a high eccentric and moderate inclined orbit (e=0.46, i=25.52°, T₉ = 2.63) and, for the previous 1000 years at least, it has been librating on a TP orbit in the L₅ area. As is illustrated in Fig. 1 (right figures, top and middle panels) near 2150, it transits from TP to QS regime. After completion 2.5 QS loops, about the year 2600, the object starts to librate in TP orbit around the L₄ lagrangian point. The amplitude of libration is 25° when 2007 GH₆ is in the TP phase and 50° in the QS phase. Near 3900 this asteroid leaves QS state and will be moving in TP-QS-TP orbit with large amplitude of σ.

Almost 1.5 year interval of observations of this asteroid is relatively short but all VOs present a very similar behavior up to 4500 year (see Fig 1, right figures, middle and bottom panels). After that moment all VOs of 2007 GH₆ start to diverge, nevertheless, about 50% of them still continue the motion in the TP-QS-TP orbit and about 4% is locked in the L₅ area until the end of the integration.

3.2. Temporary horseshoe types of orbits: asteroids 2006 QL₃⁹, 2006 SA₃₈⁷ and comet 200P/Larsen

These three objects, two asteroids and one comet, are the only known co-orbitals of Jupiter which are currently trapped in a HS orbit. As one can see in top and bottom panels of Fig. 2 and Fig. 3 their semimajor axis alternates between slightly smaller and/or slightly larger values than the outer boundaries of the co-orbital region (4.85 a.u. - 5.56 a.u.). In general, these boundaries separate HS orbits (or another types of co-orbital motion) from (irregular) passing ones. Thus, these boundaries can be interpret as the stability limits of the co-orbital motion (see also Namouni et al. (1999), Connors et al. (2004)).

2006 QL₃⁹ has very large value of eccentricity (e = 0.60), small value of inclination (i = 13.35°) and the Tisserand parameter with respect to Jupiter, T₉ =2.53. At present it is in a compound HS-QS orbit as one can see in Fig. 2 (left figures, top and middle panels). The object transited from the QS to the HS state about 1920. It stays in the HS orbit to 2330 and then the object enters a QS orbit. The asteroid has interval of observations of about 4 years. Within the predictability period (see below) the asteroid experiences a few close encounters (< 0.6 a.u.) with Jupiter. The close approach to Jupiter took place about 1600 (≈ 0.4 a.u.) and other encounters will be about 2630 and 2791 when the asteroid will pass the planet at a distance of 0.32 a.u. and 0.22 a.u., respectively. This object also experiences, because of large value of its eccentricity, close approaches with both Mars (≈ 0.6 a.u.) and Saturn
We obtained that after the close approach of 2006 QL$_{39}$ to Jupiter about the year 2790 the orbital elements start to diverge significantly and the orbit of this object becomes unpredictable. Going back in time the orbital evolution of 2006 QL$_{39}$ is predictable for about 700 years, i.e. back to the year 1300.

2006 SA$_{387}$ has moderate eccentricity ($e = 0.19$), small inclination ($i = 3.84^\circ$) and the Tisserand parameter with respect to Jupiter, $T_J = 2.89$. Its observational interval is about 6 years. The nominal orbit and all VOs show a very similar behavior within the time interval of [1780, 2250], while outside this period dynamical evolution of all VOs starts to diverge (see Fig. 2 right figure, middle and bottom panels). Within this almost five hundred year period the object executes two horseshoe loops, the first slightly outside the co-orbital region ($|\Delta a| < 1.10e$) and the second inside ($|\Delta a| < 0.95e$) (Fig. 2 right figures, top panel) as well as experiences several moderately deep ($< 0.6$ a.u.) encounters with Jupiter. Forward in time about 50% of VOs is moving on the horseshoe orbit to 2500. Then, almost all VOs leave the co-orbital region of Jupiter, however about 7% of VOs stay inside the co-orbital region to 3500 and transit between HS and TP types of motion.

200P/Larsen belongs to the Jupiter family comets. It has moderate eccentricity ($e = 0.33$) as well as inclination ($i = 12.11^\circ$), and the Tisserand parameter with respect to Jupiter is $T_J = 2.74$. Fig. 3 shows that before the year 1995 this comet was moving outside Jupiter co-orbital region. In 1995 it passed at the distance of 0.35 a.u. from the giant planet. This very close encounter with Jupiter caused the shortening of the semimajor axis of the comet orbit from 5.7 a.u. to 4.9 a.u. and a decrease in the perihelion distance from 4.0 a.u. to 3.3 a.u. Finally, the comet has started to move in an HS orbit. After its HS episode, lasting about 135 years, the transition into QS orbit will take place (around the year 2130) from the L$_5$ lagrangian point. 200P/Larsen executes two QS loops and leaves this state near 2300 and again transits into a HS regime.

Because of the moderate eccentricity 200P/Larsen do not pass very close both Mars and Saturn. The minimal distances between the comet and these planets are over 2.0 a.u. and 3.0 a.u., respectively. On the other hand, the object experiences multiple close encounters with Jupiter. The closest approaches with this planet occurred in 1917 (0.063 a.u.) and in 1995 (0.35 a.u.). The former encounter changed the semimajor axis from 8.8 AU to 5.8 AU and perihelion distance from 4.94 a.u. to 4.03 a.u.. When this comet will stay in a QS orbit (2130 -2300) the distance of 200P/Larsen from Jupiter will remain larger than $\sim 0.7$ a.u.

According to presented analysis the orbit of 200P/Larsen seems to be predictable within the time interval of [1917-2800] (Fig. 3, bottom panel). However, comparing pure gravitational evolutionary tracks for two starting nominal orbits, NG and pure gravitational, we conclude that the orbit of this comet is known well only 100 years back (after the comet encounter with Jupiter in 1917) and 230 years forward (to Jupiter close encounter in the year 2242) (see also discussion in Sect.2).
Figure 2: The same as in Fig. 1 for asteroids 2006 QL₃⁹ (left) and 2006 SA₃⁸⁷ (right).
3.3. Present quasi-satellite objects: asteroids 2001 QQ\textsubscript{199}, 2004 AE\textsubscript{9} and comets P/2002 AR\textsubscript{2} LINEAR, P/2003 WC\textsubscript{7} LINEAR-CATALINA

2001 QQ\textsubscript{199} is currently a quasi-satellite of Jupiter (Kinoshita and Nakai 2007). Its amplitude of $\sigma$ varies from 105° to 115° with libration period of about 490 years (see Fig. 4 left figures, top and middle panels). The orbital eccentricity of the asteroid is $e = 0.43$, the inclination $i = 42.48^\circ$ and the Tisserand parameter, $T_J = 2.37$. The minimum distance of the asteroid from Jupiter is larger than $\sim 1.34$ a.u. and from Mars and Saturn larger than 1.0 a.u. Kinoshita and Nakai (2007) found that around October 2013 2001 QQ\textsubscript{199} approaches to the Earth at a distance of 2.4 a.u. and they expect to detect a cometary activity of this object.

Relatively long interval of observations of about 8 years of this object and lack of deep close approaches to planets allows to determine the dynamical behavior for a long period of time. As one can see in Fig. 4 (left figures, middle and bottom panels) the nominal orbit and all VOs present a very similar behavior within the assumed time of integration i.e [0-12000] but at the end of integration the VOs start...
to slightly diverge.

2004 AE$_9$ is the second example of asteroids to be recognized as a QS of Jupiter by Kinoshita and Nakai (2007). As one can see in Table 1 this asteroid has very high eccentricity ($e = 0.64$) and very small inclination ($i = 1.65^\circ$). Its Tisserand parameter with respect to Jupiter is about 2.50. Within assumed time of integration (i.e. in years 0-12000) its eccentricity varies from 0.55 to 0.72 and the inclination decreased from 10$^\circ$ to the present value. In the future the inclination will increase up to 16$^\circ$. This object is not quite a Mars crosser, but it experiences very close encounters ($\sim 0.1$ a.u.) with this planet. The next close approach to Mars will occur in 2015 at a distance of 0.57 a.u. The distance of 2004 AE$_9$ from Jupiter and Saturn remains larger than $\sim 1.6$ a.u. and $\sim 0.5$ a.u., respectively. Kinoshita and Nakai (2007) found that in July 2015 this object will approach to the Earth within 1.81 a.u. and they predict that a cometary activity of this object can be detected.

In the QS regime the asteroid librates with amplitude of principal resonant angle $\sigma = 35^\circ - 60^\circ$ and a period of libration of about 200 years. During every QS loop its semimajor axis alternates regularly from 4.99 to 5.43 a.u. as one can see in Fig. 4 (right figures).

According to our numerical simulations the nominal orbit and all of VOs present a very similar behavior over the entire range of integration [0, 12000]. Kinoshita and Nakai (2007) showed that 2004 AE$_9$ will occupy its current QS orbit to 15000.

Comets P/2002 AR$_2$ LINEAR and P/2003 WC$_7$ LINEAR-CATALINA were found as asteroids and then a cometary activity was detected on these bodies. Both comets belong to Jupiter family comets with the Tisserand parameter of 2.52 and 2.36, respectively. These objects are currently Jupiter QS (Kinoshita and Nakai 2007). However, both comets have short interval of observations (see Table 1) what means that it is not possible to determine the NG effects for these objects. Their perihelion distances are 1.7 a.u. and 2.1 a.u. from the Sun, respectively. The evolution of the guiding center of both comets, the changes in semimajor axis and the principal resonant angle of 10 randomly selected VOs are presented in Fig. 5 within a time interval of 1000 years backward and forward. However, we must keep in mind that due to the calculated uncertainties of orbital elements, the NG effects, which can be significant in the motion of these comets, and due to the interactions with the planets, it is clear that we cannot trace the orbits of these objects with certainty over a period larger than a few hundred years.

P/2002 AR$_2$ is moving on a regular QS orbit with amplitude of the guiding center of about 50$^\circ$ deep inside co-orbital region ($|\Delta a| < 0.6\epsilon$) (Fig. 5, left figures). This comet does not experience close approaches to both Jupiter (the distance of this object from the Jupiter is larger than 2.0 a.u. during the integration period) and Saturn ($> 3.0$ a.u.) but it makes multiple relatively close approaches ($> 0.6$ a.u.) to Mars. In 2014, the comet reaches its the closest approach distance of 1.9 a.u. to the Earth.

Comet P/2003 WC$_7$ is librating in a QS orbit (right middle panel of Fig. 5).
Near 2500, the orbital elements of this comet start to diverge and a subsequent transitions into TP orbits are possible (Fig. 5, right figure, top and middle panels). Our calculations indicate that in the past and the next a few hundred years its distance from Jupiter, Saturn and Mars is never less than 2.0 a.u., 3.0 a.u. and $\sim$0.6 a.u., respectively. The comet will make its closest approach to the Earth (0.71 a.u.) in the year 2015.

Figure 4: The same as in Fig. 1 for asteroids 2001 QQ$_{199}$ (left) and 2004 AE$_9$ (right).
3.4. *Temporary captured co-orbital objects: (118624) 2000 HR$_{24}$ and 2006 UG$_{185}$*

Currently, the asteroids (118624) 2000 HR$_{24}$ and 2006 UG$_{185}$ are moving in passing-type orbits (see both middle and bottom panels of Fig. 6). They have moderate values of eccentricity and inclination (see Tab. 1) and the Tisserand parameter with respect to Jupiter is 2.80 and 2.72, respectively.

The interval of observations of (118624) 2000 HR$_{24}$ is about 50 years, thus its orbit is well known. However, due to close multiple encounters with Jupiter the swarm of VOs starts to diverge after the year 2350 and before the year 1350 as one can see in Fig. 6 (left figures, middle and bottom panels). The boundaries of the predictability time are comparable with these in Karlsson (2004). The semimajor axis of this object had been slowly increasing towards Jupiter’s value of semimajor axis and finally this object entered Jupiter’s co-orbital region near 1913 from the L$_5$ side (Fig. 6, left figures, middle and top panels). Near 2050 (118624) 2000
HR$_{24}$ will be temporarily trapped in 1:1 mean motion with Jupiter in a QS orbit as was also found by Karlsson (2004). The object leaves this state (as well as the co-orbital region of Jupiter) near 2136, completing one QS loop. In the QS state, (118624) 2000 HR$_{24}$ experiences multiple close approaches to Jupiter; the closest encounters with the planet will occur in 2095 (0.57 a.u.), 2107 (0.53 a.u.) and 2136 (0.22 a.u.).

Our calculations show that, in the near future (i.e. to 3000), about 58% of VOs have semimajor axis smaller (mostly between 4 and 5 a.u.) than that of Jupiter, in the past (i.e. in the years 1000-2000) - 71%. This behavior is also in good agreement with predictions by Karlsson (2004).

Figure 6: The same as in Fig. 1 for asteroids (118624) 2000 HR$_{24}$ (left) and 2006 UG$_{185}$ (right). In the case of (118624) 2000 HR$_{24}$ and 2006 UG$_{185}$ the time evolution of their guiding center is plotted within the time interval 2050-2150 and 2020-2080 respectively.

2006 UG$_{185}$ is the second example of an object which will be temporarily captured by Jupiter into its co-orbital area in the next 40 years. In this case, we had a significantly shorter period of 6 yr observations than for the previous object, how-
ever, the period of predictability of 2006 UG$_{185}$ seems to be comparable with that for (118624) 2000 HR$_{24}$. One can see in Fig. 6 (right figures, middle and bottom panels) that the dynamical evolution of the orbital elements of 2006 UG$_{185}$ can be predictable from 1800 to 2320. The transition into co-orbital orbit occurs around 2045 and lasts about 15 years. The co-orbital part of the motion is visible in Fig. 6 (right figures, top and middle panels) as a one revolution of the guiding center with small value of the principal resonant angle ($|\sigma| < 1^\circ$). During the co-orbital episode 2006 UG$_{185}$ remains within the distance of 2.0 a.u. from Jupiter. In this state it makes closest approach to Jupiter near 2056, passing at a distance of about 0.31 a.u. from the planet. Although its guiding center enclosed origin (smaller left loop at Fig. 6, right figure, top panel), this object is not captured in a QS orbit. In the QS orbit an object should stay about 12 at least (orbital period of Jupiter) - the smaller left loop of 2006 UG$_{185}$ last about 6 years (2045-2051).

In the past, i.e. in the years 1000-2000, 81% of VOs had a semimajor axis smaller than that of Jupiter and did not experiences co-orbital episodes. In the future, after leaving the co-orbital temporary capture state, until the end of our integration the fraction of these objects drops to just 23%. The remaining VOs may be captured into co-orbital area.

4. Summary and discussion

We have analyzed the orbits of six already known, and we have identified five new non-Trojan, co-orbitals of Jupiter. These object have been divided into several classes according to their dynamical properties. We selected four such classes of the co-orbital behavior of the objects: TP/QS, HS/QS, long lasting QS and temporary co-orbitals. The most important results of our investigation are summarized in the Table 2. In this table are listed the Tisserand parameter with respect to Jupiter, the type of co-orbital motion, time of integration and the estimated period of predictability of the all considered objects.

The analyzed objects can also be classified according to their Tisserand parameter with respect to Jupiter, $T_J$. According to this criterion cometary orbits are defined as those having $T_J < 3$, while asteroidal orbits are those with $T_J > 3$. Therefore, all the objects with $T_J < 3$ that do not present any signature of cometary activity are defined as an asteroids in cometary orbits (ACO) (Licandro et al. 2006). They also found that ACO with $T_J > 2.9$ have spectra typical of the main belt objects while those with $T_J < 2.9$ shown comet-like spectra. All objects investigated here have $T_J < 2.9$, with the largest value of $T_J = 2.89$ for asteroid 2006 SA$_{387}$.

The three analyzed comets belong to the Jupiter family comets ($T_J > 2.0$) and, as one can see in the Table 2, the Tisserand parameter of analyzed asteroids also locate all of them as Jupiter family comets. In fact, the comets P/2003 WC$_7$ LINEAR-CATALINA and P/2002 AR$_2$ LINEAR were discovered as asteroids 2003 WC$_7$ and 2002 AR$_2$, and later a cometary activity was recognized on
Table 2: The Tisserand parameter, type of co-orbital behavior, integration and predictability period for the analyzed objects.

| Object              | $T_T$ | Dynamical behavior | Integration period | Predictability period from to |
|---------------------|-------|--------------------|-------------------|-----------------------------|
| (241944) 2002 CU$_{147}$ | 2.60  | transient TP-QS    | 1000-7000         | <1000 6500                  |
| 2007 GH$_6$         | 2.63  | transient TP-QS, compound TP-QS-QP | 1000-7000         | <1000 5500                  |
| 2006 QQ$_{39}$      | 2.33  | temporary compound HS | 1000-5000         | 1200 2511                   |
| 2006 SA$_{387}$     | 2.83  | temporary HS       | 1000-5000         | 1350 2250                   |
| 2001 QQ$_{39}$      | 2.97  | long-lasting QS    | 0-12000           | <0 12000                    |
| 2004 AE$_9$         | 2.50  | long-lasting QS    | 0-12000           | <0 12000                    |
| C/2002 AR$_2$ LINEAR | 2.52  | compound TP-QS     | 1000-5000         | 1350 2250                   |
| 2006 UG$_{185}$     | 2.27  | temporary co-orbital | 1000-5000         | 1800 2520                   |
| 2008 Larsen         | 2.74  | transient QS-HS    | 1000-5000         | 1977 2600                   |
| C/2005 ME$_7$ LINEAR | 2.52  | long-lasting QS    | 1000-5000         | <1400 7500                  |
| C/2003 WC$_7$ LINEAR-Catalina | 2.36  | compound TP-QS-QS-QS | 1000-5000         | 1300 2500                   |

The predictability period mainly depends on the close approaches with the Jupiter. As we can see in table 2 the most predictable orbits have objects which avoid close encounters with this planet, i.e. (241944) 2002 CU$_{147}$, 2007 GH$_6$, 2001 QQ$_{39}$ and 2004 AE$_9$. The three identified horseshoe librators 2006 QQ$_{39}$, 2006 SA$_{387}$ and 200P/Larsen have short predictability period mostly due to the specific dynamic of horseshoe orbit. When an object is moving on a HS orbit, it has large amplitude of libration and experiences close multiple encounters with the planet (even if its eccentricity is small). This generates instability of the object’s orbit and one can expect that such an asteroid is expelled from the co-orbital region after a few HS libration periods (see also discussion in Stacey and Connors (2008), section 4.1 therein). Indeed, according to our analysis these three objects execute a few HS loops (in the case of 2006 QQ$_{39}$ and 200P/Larsen the HS state is interrupted by QS behavior) before leaving this state, as well as the planet’s co-orbital region. The comets P/2002 AR$_2$ LINEAR and P/2003 WC$_7$ LINEAR-Catalina do not experience close encounters with Jupiter. On the other hand, these objects can close approach to Mars. Additionally, these comets have very short observational intervals. For these reasons the predictability period of these object is short. Asteroids (118624) 2000 HR$_{28}$ and 2006 UG$_{185}$ experience close encounters with Jupiter and they have relatively short predictability time interval. These objects also remain in the co-orbital region at most a few hundred of years. We conclude that the objects that experience close encounters with the Jupiter may be delivered into the co-orbital region from different parts of the Solar System, for example from either the Trojan area of external part of the System and they leave the co-orbital region relatively quickly (within a few hundred years). Kortenkamp and Joseph (2011) found that the Jupiter Trojans were able to migrate to QS orbits during the late stages of migration of the giant planets, however, it seems that current QS of this planet entered into this state later. The main reason is that the mechanism of transforming TP orbit into QS orbit was not efficient (about 0.2% of the escaping Jupiter Trojan particles entered in QS after leaving the Trojan region within a few milion of years) and the QS of Jupiter can persist in this state at most
Thus, the present QS entered into this state likely a few millions year ago or less.

We have shown that 2007 GH$_6$ is currently a QS of Jupiter for about 200 years and it leaves this regime about 2030 transiting into TP orbit. In general, this object stays within the co-orbital region (all VOs remain in this area) and it jumps between QS and TP types of orbits. Similar dynamics demonstrates 2007 GH$_6$, however, according to our calculations after 3900 it will be moving in TP-QS-TP orbit with large amplitude of the guiding center. This object has been observed for a short time interval of about 1.33 yr but it exhibits unexpectedly very long predictability period. The orbit of 2007 GH$_6$ is predictable to $\sim 4500$. After that time the object is still locked in a 1:1 mean motion resonance with Jupiter to the end of integration.

In this paper the detailed analysis of the four QS objects, i.e. two asteroids (2001 QQ$_{199}$ and 2004 AE$_9$) and two comets (P/2002 AR$_2$ LINEAR and P/2003 WC$_7$ LINEAR-CATALINA) found by Kinoshita and Nakai (2007) have been presented. For both asteroids our results fully agree with the conclusions drawn by Kinoshita and Nakai (2007). This is especially worth emphasizing because asteroid 2001 QQ$_{199}$ was observed after the year 2007, thus for this object we used significantly richer observational material than Kinoshita and Nakai (2007). Since the NG effects may affect the dynamical behavior of comets P/2002 AR$_2$ and P/2003 WC$_7$ we decided to integrate their orbits only 1000 years backward and forward. Within this period of integration all VOs of the first comet does not diverge significantly and all VOs shows QS behavior. In the case of P/2003 WC$_7$ we have shown that this object is a QS of Jupiter to the year 2500 at least. After that time the orbital elements of this comet starts to diverge and according to presented calculations the transitions between QS and TP orbit can take place. The main reasons why the predictability period of this object is very short seems to be that the comet has only about 0.5 yr interval of observations and the large eccentricity. Although P/2003 WC$_7$ does not pass close to Jupiter (all encounters are over 2.0 a.u.), it is able to experience very close encounters with Mars and the Earth due to the very eccentric orbit ($e=0.68$).

We have confirmed the results of Karlsson (2004) that (118624) 2000 HR$_{24}$ will be temporarily captured by Jupiter on a QS orbit near 2050 and that the object 2006 UG$_{185}$ will be captured into co-orbital region of Jupiter around 2045, however, in contrary to his predictions, this asteroid is not co-orbital of Jupiter, presently. Its guiding center encloses the origin but this object will not a QS of Jupiter. Currently, these objects do not librate in a 1:1 mean motion resonance with Jupiter. This behavior causes that (118624) 2000 HR$_{24}$ and 2006 UG$_{185}$ repeatedly are coming close to Jupiter and therefore their predictability period is of order of a few hundred years.
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