Dynamics of inclined and eccentric orbits in the 1:1 mean motion resonance with Jupiter

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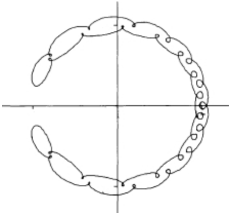

Introduction

- Levison et al., 1997, Tsiganis et al., 2005 found that the Trojan swarms are not indefinitely stable and they can escape from the L_4 and L_5 clouds
- Centaurs may be temporarily captured into the co-orbital region of the giant planets, especially of Jupiter (Horner and Wyn Evans, 2006)
- Karlsson (2004) found a few examples of asteroids and comets which show such behavior
- Kinoshita and Nakai (2007) identified four QS of Jupiter

Co-orbital region and co-orbital motion

- $|a_P - a| \leq \epsilon$, where a and a_P are respectively the object's and planet's orbital semimajor axes, ϵ - the radius of the Hill's sphere ($\epsilon = 0.35$ AU for Jupiter)
- In case of Jupiter co-orbitals: 4.85 AU$\leq a \leq$ 5.56 AU

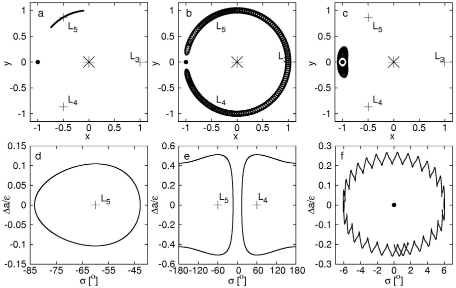

FIGURE: Classical co-orbital motion:a - tadpole (TP),b - horseshoe (HS), c - quasi-satellite orbits (QS), where $\Delta a = a_P - a$, $\sigma = \lambda - \lambda_p$, is the principal resonant angle, λ, λ_p - the mean longitudes of the asteroid and the planet, respectively

Co-orbital region and co-orbital motion

- For sufficiently large values of the eccentricity and the inclination compound (they correspond to the merger of HS or TP orbits with QS orbits) and transient orbits (i.e. transitions between different types of co-orbital motion occur) can exist (Namouni, 1999)

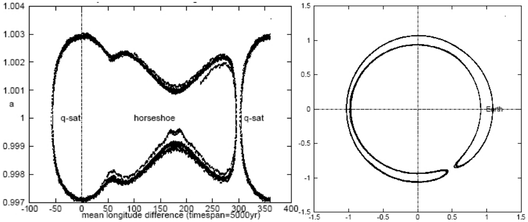

FIGURE: An example of compound HS-QS orbit. Left: the orbit of Cruithne in a $(\Delta a - \sigma)$ coordinates (averaged over 1 yr). Right: mean motion (averaged over 1 yr) of asteroid Cruithne with respect to Earth in a co-rotating frame. Taken from Wiegert and Innanen (1998).

Non-Trojan co-orbitals in the Solar System

- Terrestial planets:
  - Venus: 2002 VE_{68} (QS), 2001 CK_{32} (compound HS-QS)
  - Earth: 2002 AA_{29} (transient HS-QS), 2004 GU_9, 2006 FV_{35} (QS), 2003 YN_{107} (QS from 1997 to 2006), Cruithne (compound HS-QS), 2010 SO_{16} (HS)
  - Mars: 36017 (1999 ND_{43}) (HS)
- Main Belt:
  - Christou (2000) showed that the dwarf planets (1) Ceres or (4) Vesta can maintain smaller asteroids in the co-orbital resonance at least temporarily.
- Giant planets:
  - Jupiter: 2001 QQ_{199}, 2004 AE_9, P/2003 WC_7 LINEAR-CATALINA, P/2002 AR_2 LINEAR (QS)
  - Saturn: Saturn's moons Janus and Epimetheus occupy HS orbits with respect to each other

Selection of objects

- We looked for objects located in the Jupiter co-orbital area
- We selected 3160 asteroids and 24 comets
- 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 point (are not Trojans)
- Finally, we expanded the asteroid search to objects whose semi-major axes satisfy the condition: $\epsilon < |\Delta a| < 2\epsilon$
- Analysis of motion of the objects was performed based on a sample of 201 cloned orbits (virtual objects, VO) created from initial coordinates and velocities of the nominal osculating orbit and generated by Sitarski's orbital program package (Sitarski, 1998)

Selected objects

TABLE: Osculating orbital elements of examined co-orbital objects. Epoch: April 10, 2007 (JD 2454200.5), Equinox: J2000.0.

Object	a [AU]	e	$i[^\circ]$	$\Omega[^\circ]$	$\omega[^\circ]$	$M[^\circ]$	arc (yrs)
(241944) 2002 CU_{147}	5.23	0.31	32.90	315.01	60.86	338.36	12
2007 GH_6	5.30	0.46	25.52	79.17	97.57	109.15	1.5
2006 QL_{39}	5.12	0.60	13.35	172.51	253.91	106.35	4
2006 SA_{387}	5.03	0.19	3.84	130.73	199.14	149.07	6
2001 QQ_{199}	5.33	0.43	42.48	213.09	192.86	249.18	8
2004 AE_9	5.11	0.64	1.65	188.70	285.78	204.87	0.25
(118624) 2000 HR_{24}	4.96	0.17	15.52	223.42	353.92	334.28	50
2006 UG_{185}	4.83	0.12	20.02	131.78	301.23	168.93	6
200P/ Larsen	4.91	0.33	12.12	234.80	133.89	63.00	12
C/2002 AR_2 LINEAR	5.35	0.62	21.10	7.70	73.25	248.90	0.25
C/2003 WC_7 LINEAR-Catalina	5.20	0.68	21.43	88.80	342.22	196.74	0.42

(241944) 2002 CU_{147} and 2007 GH_6

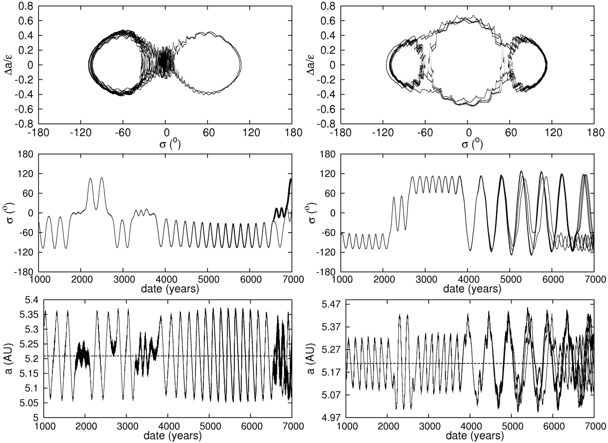

FIGURE: Asteroids 2002 CU_{147} (left) and 2007 GH_6 (right). Top: evolution of the guiding center of the asteroid. The time interval is the same as in the case of both middle and bottom panels, middle: evolution of the principal resonant angle of the representative subsample of 10 VOs (nominal orbit plus 9 randomly selected VOs), bottom: evolution of the semimajor axis of 10 VOs. The dashed line indicates the semimajor axis of Jupiter

2006 QL_{39} and 2006 SA_{387}

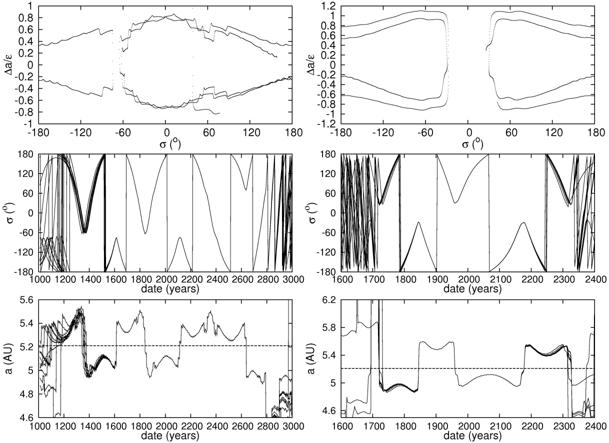

FIGURE: The same as in Fig. 1 for asteroids 2006 QL_{39} (left) and 2006 SA_{387} (right)

200P/Larsen

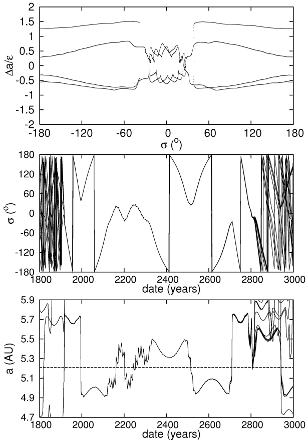

FIGURE: The same as in Fig. 1 for comet 200P/Larsen

2001 QQ_{199} and 2004 AE_9

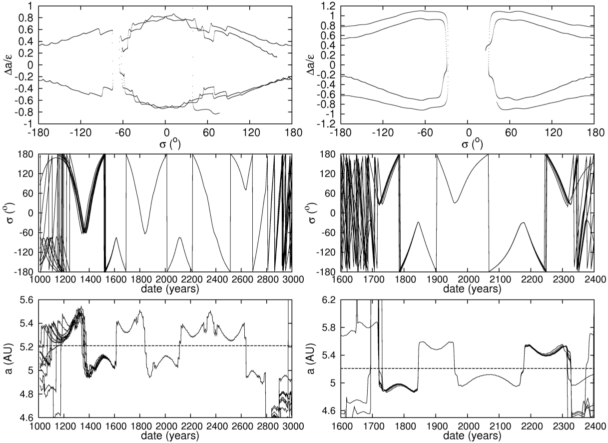

FIGURE: The same as in Fig. 1 for asteroids 2001 QQ_{199} (left) and 2004 AE_9 (right)

P/2002 AR_2 LINEAR and P/2003 WC_7 LINEAR-CATALINA

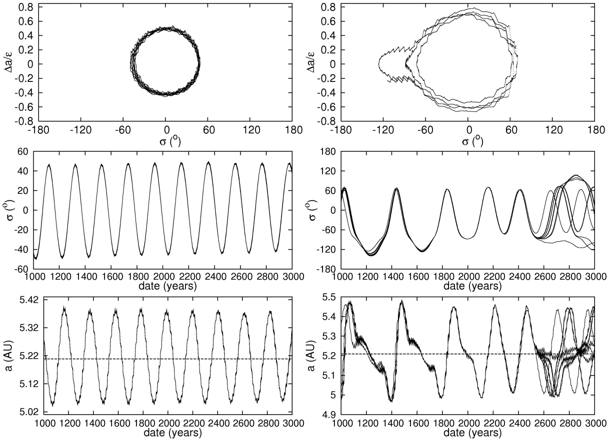

FIGURE: The same as in Fig. 1 for comets P/2002 AR_2 LINEAR (left) and P/2003 WC_7 LINEAR-CATALINA (right).

2000 HR_{24} and 2006 UG_{185}

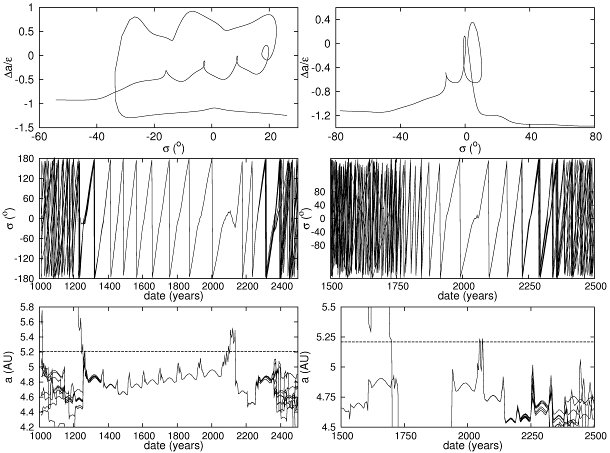

FIGURE: The same as in Fig. 1 for asteroids (118624) 2000 HR_{24} (left) and 2006 UG_{185} (right). In the case of these objects the time evolution of their guiding center is plotted within the time interval 2050-2150 and 2020-2080 respectively.

Summary

TABLE: The Tisserand parameter, type of co-orbital behavior, integration and predictability period for the analyzed objects.

Object	T_J	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-TP	1000-7000	<1000	5500
2006 QL_{39}	2.53	temporary compound HS	1000-3000	1200	2791
2006 SA_{387}	2.89	temporary HS	1000-3000	1700	2200
2001 QQ_{199}	2.37	long-lasting QS	0-12000	<0	>12000
2004 AE_9	2.50	long-lasting QS	0-12000	<0	>12000
(118624) 2000 HR_{24}	2.80	temporary QS	1000-3000	1600	2350
2006 UG_{185}	2.72	temporary co-orbital	1000-3000	1800	2320
200P Larsen	2.74	transient QS-HS	1000-3000	1917	2800
C/2002 AR_2 LINEAR	2.52	long-lasting QS	1000-3000	<1000	>3000
C/2003 WC_7 LINEAR-Catalina	2.36	compound TP-QS/QS	1000-3000	1200	2500

- Asteroids in cometary orbit (ACO): $2 < T_J < 3$
- Licandro et al., 2006 found that ACO with $T_J > 2.9$ have spectra typical of the main belt objects while those with $T_J < 2.9$ show comet-like spectra