DYNAMICAL BEHAVIOUR OF ASTEROIDS IN THE 4:1 RESONANCE

FRANCISCO LÓPEZ-GARCÍA

Observatorio Astronómico, Av. Benavidez 8175-oeste, 5413 Chimbas,San Juan, Argentina

and

ADRIAN BRUNINI

Fac. de Ciencias Astron.y Geofís., Paseo del Bosque s/n, 1900 La Plata, Argentina

We study the dynamics of mean motion resonance with Jupiter in the 4:1 gap using only gravitational methods. This mechanism is capable of explaining this Kirkwood gap in an uniform way (see Ferraz-Mello, 1994; Ferraz-Mello et al., 1994; Moons, 1997; Yoshikawa, 1989). We considered the asteroidal motion in two and three dimensions and we carried out our investigations integrating numerically the full equations of motion and taking into account Mars, Jupiter and Saturn as disturbing planets. The orbital evolution of asteroids was obtained considering the elements variation. The numerical investigations were carried out using symplectic integrators. These integrations were stopped when the asteroid had close encouters with Mars or Jupiter, this occurs when the distance between the planet and the asteroid is of the order of 0.01 AU or less, or when the eccentricity increases up to 0.9. We studied real and fictitious asteroids on a time scale of 5×10^7 yr. The initial osculating elements of perturbing planets and their inverse masses were taken from the Ephemerides of Minor Planets (EMP) at the epoch of JD 2450000.5. The initial data corresponding to the real asteroids were also taken from the EMP. The starting elements of fictitious asteroids were, in all analyzed cases, $a = a_{crit} = 2.064 AU$, $i = 2°.5$ and $e = 0.01$ (in the majority of cases). The other initial elements are shown in Table II. We have also studied fictitious asteroids with $i = 0°$, $a = a_{crit}$ and $e = 0.01$ (Table I). The present analysis leads to the following results: (1) The motions are unstable. The eccentricity, in the majority of cases, has very large increase. It may grow up to 0.9 in 10^6 yr. The semi major axis has large variations then, owing to both effects some fictitious asteroids reach the 3:1 resonance while others reach 7:2 resonance in a few million years, they are very chaotic regions. (2) The eccentricities of fictitious asteroids become large by the effect of the secular resonance ν_6, i.e. when $(\varpi - \varpi_{Sat}) \cong 0$, the rate

TABLE I

All bodies, planets and fictitious asteroids, with i = 0°, a_{crit} = 2.064 AU

Fict. Ast.	e	Ω°	ω°	M°	T(f) yr.	Comments
BF01	0.01	0.0	195.0	0.0	< 2.5E+6	$(\varpi - \varpi_{jup}) = \pi$, Mars crosser, reaches the 3:1 resonance.
BF02	0.01	0.0	190.0	0.0	< 2.2E+6	Ejection, reaches the 3:1 resonance.
BF03	0.01	0 .0	185.0	0.0	2.0E+6	Ejection, temporarilly captured by Mars.
BF04	0.01	0.0	180.0	0.0	2.1E+6	Ejection, reaches the 3:1 resonance.
BF05	0.01	0.0	175.0	0.0	3.0E+6	Ejection, reaches the 3:1 resonance.
BF06	0.01	0.0	185.0	180.0	7.2E+6	Irregular motion, a jumps to 2.2567 AU, agrees with 7:2 resonance. Ejection.
BF07	0.01	90.0	90.01	80.0	2.2E+6	Ejection.
BF08	0.30	0.0	185.0	180.0	2.0E+6	Ejection.

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TABLE II

Fictitious asteroids, a_{crit} = 2.064 AU, all with i = 2°.5

Fict. Ast.	e	Ω°	ω°	M°	T(f) yr.	Comments
AF01	0.01	90.0	105.71	250.0	1.E+7	$(\varpi - \varpi_{jup}) = \pi$, full stable motion
AF02	0.01	90.0	105.71	70.0	5.E+7	Regular motion up to 1.E+7 yr, later the motion finishes in 7:2 resonance, a_{crit} =2.25 UA., ejection.
AF03	0.01	90.0	105.71	0.0	< 8.6 E+6	$(\varpi - \varpi_{jup}) = \pi$, chaotic motion, reaches the 3:1 resonance.
AF04	0.01	90.0	105.71	180.0	6.9 E+6	$(\varpi - \varpi_{jup}) = \pi$, ejection
AF05	0.30	90.0	90.0	180.0	2.E+7	Temporarilly captured by Mars, e approachs to 1 for some time.
AF06	0.25	90.0	90.0	180.0	< 2.3 E+6	Ejection
AF07	0.01	8.214	7.5	0.0	2. E+7	$(\varpi - \varpi_{jup}) = 0$, stable motion, a jumps to 2.36 AU, $e < 0.35$
AF08	0.01	8.214	7.5	180.0	5.E+7	$(\varpi - \varpi_{jup}) = 0$, no regular motion, temporarilly captured by Mars. $i < 0.4$ rad.
AF09	0.30	8.214	7.5	0.0	< 1. E+7	$(\varpi - \varpi_{jup}) = 0$, chaotic motion, reaches the resonance
AF10	0.30	8.214	7.5	180.0	3.E+7	$(\varpi - \varpi_{jup}) = 0$, temporarilly captured by Mars, $e < 0.5$, $i < 0.25$ rad.
AF11	0.01	100.0	275.0	250.0	5.E+7	Ω, ω, M equal to Jupiter's, regular motion, $e < 0.06$, $i < 0.05$ rad.
AF12	0.01	100.0	275.0	70.0	5.E+7	Ω, ω equal to Jupiter's, the motion is fully regular, a nearly constant, $e < 0.06$, $i < 0.05$
AF13	0.01	100.0	275.0	180.0	< 7.2E+6	Ω, ω equal to Jupiter's, $e \to 1$, close approach to Jupiter's. Δ = 4.974 AU.
AF14	0.01	100.0	275.0	215.0	< 6.8E+6	Ejection, close approach to Jupiter.
AF15	0.01	100.0	275.0	270.0	5.E+7	The motion is nearly regular
AF16	0.01	100.0	275.0	260.0	< 2.E+6	Ejection
AF17	0.01	100.0	275.0	280.0	< 9.2.E+6	Ejection
AF18	0.01	100.0	275.0	290.0	5.E+7	Regular motion, after 2.E+6 yr. a = 2.235 UA, $e < 0.25$, $i < 0.07$ rad.
AF19	0.01	7.2	8.5	180.0	< 5.2 E+6	Ejection
AF20	0.15	90.0	90.0	180.0	< 2.5 E+6	Chaotic motion, reaches the 3:1 resonance
AF21	0.01	0.0	185.0	0.0	< 2.6E+7	(i = 0). Up to 1.E+7 yr. the motion is regular, then a decreases to 1.5 UA and finally ejection
AF22	0.01	90.0	90.0	180.0	1.5E+7	Chaotic motion, reaches the 3:1 resonance.
AF23	0.01	25.0	25.0	36.05	1.E+7	Full stable motion. $\Delta a \cong 0.01$ AU, $\Delta e \cong 0.03$

of this resonance is 26.217 "/year with period $\sim 4.9 \times 10^4$ years (Bretagnon, 1974). (3) The fictitious asteroids studied with $a = a_{crit}$, $e < 0.05$ and $i < 3°$ are removed of this gap mainly by the effects of the secular resonances ν_6 and ν_{16} (see Moons and Morbidelli, 1995; Williams, 1969). (4) There are close encounters with Mars or eventually with the Earth (not considered here) in a time scale of 10^6 - 10^7 yr. (5) For certain initial conditions some fictitious asteroids are temporally captured by Mars and in some cases for a long time. (6) If $a = a_{crit}$, $e = 0.3$ and the inclination is less than 3°, Mars and asteroid's perihelion are very close ($\sim 0.06AU$). This situation helps the capture. (7) The (a,e)-plane was used to determine the dynamical behaviour of all asteroids and we found that the 4:1 resonance is very strong. The Lyapunov times are very short.

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