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The effect of secular resonances in the asteroid region between 2.1 and 2.4 AU

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Abstract.

The asteroid region between 2.1 and 2.4 AU appears to be depopulated at inclinations $i > 12°$. This region is surrounded by the three main secular resonances ν_5, ν_6 and ν_{16} and is crossed by higher order secular resonances. Secular resonances appear to overlap in this region. Numerical integrations of the orbits of seventeen fictituous asteroids with initial inclinations $12° \leq i \leq 20°$ show that: (1) this particular asteroid region is not depopulated in our computer experiment on timescales of 2.7 Myrs; (2) inclinations are pumped up by successive crossings through higher order secular resonances while eccentricities are not increased sufficiently to produce planet-crossers; (3) bodies located in the bordering ν_6 resonance with semi-major axes a$\leq$ 2.4 AU become Earth-crossers on a time scale of 1Myr; (4) we confirm Milani and Kneževič's result (1990 Cel. Mech. 49, 247) that modes due to higher order secular resonances must be eliminated when proper elements are computed.

1 Introduction.

Morbidelli and Henrard (1991) developed a semi-numerical secular perturbation theory which allows to map locations of the principal and also of higher order secular resonances (fig.1). Morbidelli and Henrard's approach avoids any expansion of the main term of the Hamiltonian with respect to the eccentricity or the inclination of the perturbed body. Suitable action-angle variables are introduced which take into account properly the dynamics of the perihelion argument of the perturbed body. Thus, the theory is valid for large inclinations and eccentricities.

According to fig.1, the region between 2.1 and 2.4 AU is depopulated for inclinations $i \geq 12°$. This region is surrounded by the three main secular resonances ν_5, ν_6 and ν_{16}. The respective secular arguments are:

$$\varpi - \varpi_J, \qquad \varpi - \varpi_S, \qquad \text{and } \Omega - \Omega_J.$$

This depopulated region is crossed by the three higher order resonances R4, R9, R11 (the enumeration was originally introduced by Milani and Kneževič (1990)):

$$\text{R4: } (\varpi - \varpi_J) + (\Omega - \Omega_J)$$
$$\text{R9: } (\varpi - \varpi_J) + (\varpi - \varpi_S)$$
$$\text{R11: } (\varpi - \varpi_S) - (\Omega - \Omega_J)$$

In order to investigate the influence of the secular resonances in this region, we integrated over $2.7 Myrs$, the orbits of four sets of fictituous bodies with the respective starting semi-major axes: a = 2.1, 2.2, 2.3, and 2.4 AU. The integrations were carried out in the frame of the four body model: Sun – Saturn – Jupiter – small body. The DVDQ integrator of Krogh (1970) was used.

The two first sets contain 5 bodies with starting inclinations varying from $i = 12°$ to $i = 20°$ with an increment of $\Delta i = 2°$. The initial inclinations for the third set ($a = 2.3$ AU) containing 4 bodies range from 14° to 20°, while for the fourth set ($a = 2.4$ AU) the starting inclinations vary from 16° to 20° with the same increment $\Delta i = 2°$.

This gives a total of 17 bodies. All the bodies have the same starting eccentricity $e = 0.14$.

2 Results.

We now discuss the orbital evolutions of the bodies considering the different sets.

Set 1:

The two first bodies with respective starting inclinations of 12° and 14° cross the secular resonances R11, ν_{16}, and finally R9. The inclinations are gradually pumped up to 30° and 28°, respectively.

The three remaining bodies are located from the beginning in the ν_{16} secular resonance. Their resonance argument $\Omega - \Omega_J$ librates around 180°. The inclinations suffer large oscillations up to 28°.

The eccentricities of these five bodies remain comparatively small with a maximum value of $e = 0.19$.

Set 2:

The body with the starting inclination of $i = 12°$ librates temporarily in the ν_6 secular resonance. Its resonance argument $\varpi - \varpi_S$ librates, as predicted by Morbidelli and Henrard, around 0°. During this period, the eccentricity varies between 0. and 0.30, while the inclination oscillates between $12° \leq i \leq 15°$.

The bodies with respective starting inclinations $i = 16°, 18°$ and $20°$ have qualitatively similar orbital evolutions. All three are located at the beginning in the higher order resonance R11, R9, and R4 respectively, and later enter the main secular resonance ν_{16}. The inclinations are pumped up. The body with starting inclination $i = 18°$ repeatedly enters and leaves the higher order resonance R9 during the time interval $0 \leq t \leq 1.5 * 10^6$ years. At $1.5 * 10^6$ years, this body leaves R9 and enters the ν_{16} resonance region. During the time interval $1.9 * 10^6 \leq t \leq 2.7 * 10^6$ the body is located in three resonances, namely in ν_{16}, R4 and ν_5. Entering this overlapping region, the inclination increases and oscillates between 29° and 34° (Fig.2).

The body with $i = 20°$ leaves the resonance ν_{16} and enters the overlapping region of the resonances ν_5 and R4. Like in the former cases, the inclination becomes large; i varies between 30° and 35°.

During the integration time of 2.7 Myrs, the eccentricities remain bounded, not exceeding $e = 0.22$. Hence, no planetary crossing occurs.

Set 3:

The body with $i = 14°$ is a ν_6 secular resonance case. The resonant argument $\varpi - \varpi_S$ librates around 0°. The eccentricity suffers large oscillations , i.e. $0.0 \leq e \leq 0.7$, while the maximum of inclination is 25°. The body becomes an Earth-crosser over a timescale of $t \simeq 1 Myr$.

During 2.7 Myrs, the body with $i = 18°$ is located in the R11 resonance. The secular argument $(\varpi - \varpi_S) - (\Omega - \Omega_J)$ librates around 0°. There are neither large variations in eccentricity ($0.03 \leq e \leq 0.2$) nor in inclination ($17^\circ \leq i \leq 22^\circ$). A long periodic oscillation with a period $T \simeq 15 * 10^5$ years appears in eccentricity and in inclination. This result shows that the higher order secular resonances affect the orbital elements, and have, as pointed out by Milani and Knežević (1990), to be taken into account in calculating the proper elements.

Set 4:

Only one body presents a peculiar behaviour. Until $9*10^5$ years, the body with $i = 16^\circ$ is located in the ν_6 secular resonance. The argument $\varpi - \varpi_S$ librates around 0°, then it stays in the neighbourhood of 180° for a period of more than 1.5 Myr, then the body becomes an outer circulator. The eccentricity is maximum $e \simeq 0.87$ when the transitions occur, namely at $t \simeq 0.9*10^6$ years and again when the body becomes an outer circulator ($t \simeq 2.5 * 10^6$ years). The inclination varies also very strongly around the transition states. During the periods $0.5 * 10^6 yrs \leq t \leq 1 * 10^6 yrs$ and $1.9 * 10^6 yrs \leq t \leq 2.7 * 10^6 yrs$, i oscillates between 10° and 40°. Outside these time intervals, i varies in the range $16^\circ \leq i \leq 18^\circ$. We would like to point out that even at semi-major axes of 2.4 AU, bodies located in/or close to the secular resonance ν_6 may become Earth-crossers in less than 1Myr.

3 Conclusions

These numerical computions have confirmed the locations of secular resonances determined by Morbidelli and Henrard (1991) and, in particular, the overlapping of the resonances ν_5, ν_{16} and R4 at high inclinations $i \geq 30^\circ$. The passage of bodies through different secular resonances seems to pump up their inclinations. This phenomenon may be a possible mechanism to produce highly inclined Apollo-Amor objects. It also may explain the very low density of asteroids for semi-major axes $a \leq 2.3$ AU and inclinations $12^\circ \leq i \leq 30^\circ$.

Taking into account our previous results (Scholl and Froeschlé 1991), we conjecture that the secular resonance ν_6 is a good candidate to produce Earth-crossers for semi-major axes $2.0 \leq a \leq 2.4AU$ on time scales of at least 1 Myr.

The higher order secular resonances affect, as found previously by Milani and Knežević (1990), the determination of proper elements.

It is well known that overlapping resonances are in general associated with chaotic regions. It is an open problem whether or not the overlapping of main and higher order resonances produces planet-crossers. The bodies in our experiment do not become planet-crossers except those which are located in the ν_6 resonance. Of course, it is hard to guess what could happen over a much longer time scale than $2.7 * 10^6$ years. Much longer extended experiments are needed to explain completely the depletion of the considered region.

References

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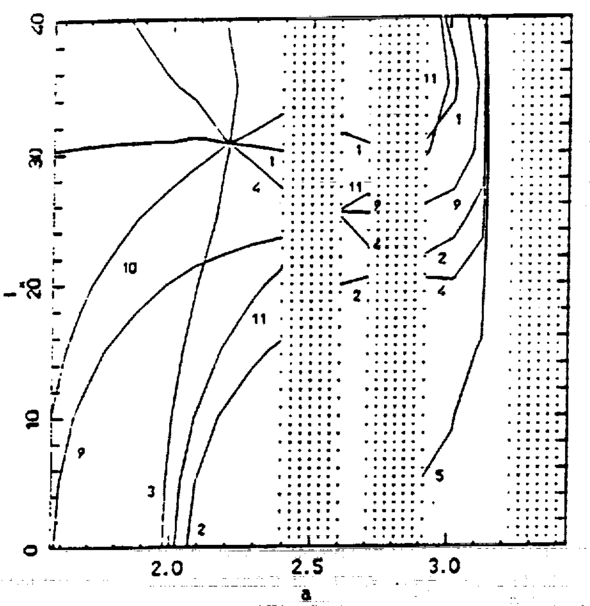

Fig.1. The locations of the secular resonances (taken from Morbidelli and Henrard 1991) ν_5, ν_6, ν_{16}, R4, R9 and R11 are labeled respectively by the numbers 1, 2, 3, 4, 9 and 11. The shaded areas are regions of overlapping with the mean motion resonances 3:1, 5:2 and 2:1.

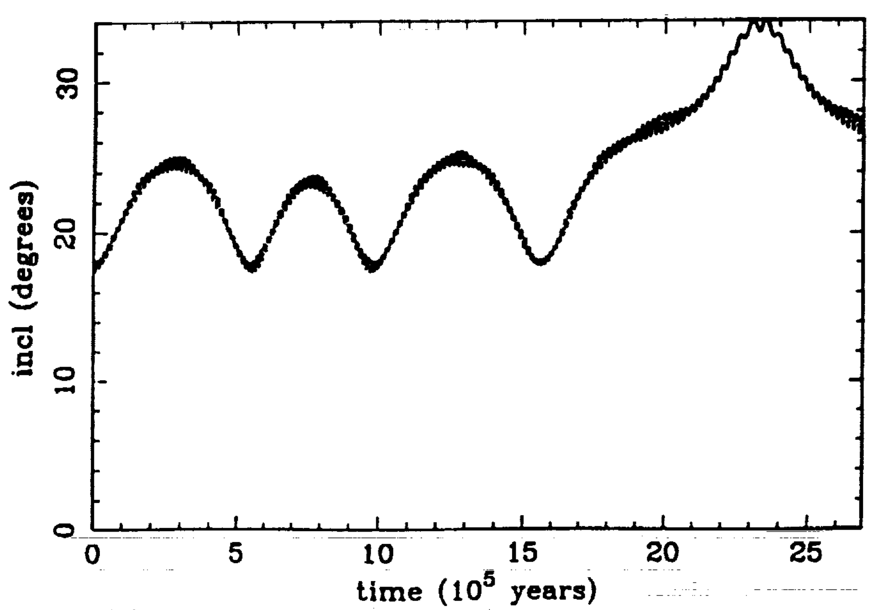

Fig.2. Time evolution of a body with starting osculating elements: a=2.2 AU, e=0.14, i= 18°. The body crosses the secular resonances ν_{16}, R4, and ν_5.

Figure Captions

Fig.1. The locations of the secular resonances (taken from Morbidelli and Henrard 1991) ν_5, ν_6, ν_{16}, R4, R9 and R11 are labeled respectively by the numbers 1, 2, 3, 4, 9 and 11. The shaded areas are regions of overlapping with the mean motion resonances 3:1, 5:2 and 2:1.

Fig.2. Time evolution of a body with starting osculating elements: a=2.2 AU, e=0.14, i= 18°. The body crosses the secular resonances ν_{16}, R4, and ν_5.