AN INTERPLANETARY MISSION TO NEPTUNE SYSTEM: ON THE DYNAMICS OF NEPTUNE SYSTEM ORBITER

Tadashi Yokoyama
UNESP IGCE DEMAC Caixa Postal 178, CEP 13.500-970 Rio Claro (SP) Brasil
tadashi@rc.unesp.br

Carlos Renato Huaura Solórzano
Departamento de Mecânica e Controle – INPE
C.P. 515, CEP 12201-970 - São José dos Campos – SP - Brazil
renato@dem.inpe.br

Antônio Fernando Bertachini de Almeida Prado
Departamento de Mecânica e Controle - INPE
C.P. 515, CEP 12201-970 - São José dos Campos – SP – Brazil
prado@dem.inpe.br

Silvia Giuliatti Winter, Othon Cabo Winter
UNESP FEG Grupo de Dinâmica Orbital e Planetologia da UNESP, Caixa Postal 205, CEP 12.516-410 Guaratinguetá (SP) Brasil
silvia@ feg.unesp.br, ocwinter@feg.unesp.br

Marcos Tadeu dos Santos
UNESP IGCE DEMAC Caixa Postal 178, CEP 13.500-970 Rio Claro (SP) Brasil
mtsantos@rc.unesp.br

Abstract. *A recent NASA report ranks a mission to Neptune System in the top of the priorities of the NASA's Solar System Exploration Theme. Due to the rich scientific return and connections to several other fields, Hammel et al (2002) propose in details, the main targets of this mission. In spite of the cost, these authors claim that the core of this mission is a Neptune system orbiter and not only a flyby passage. The authors also mention that short of exploring Pluto (the remotest planet) exploring Triton may provide better scientific return. In this work we give the basic dynamics of a particle (spacecraft) in the Neptune system, in particular an orbiter around Triton. Neptune-Triton system is unique in our solar system: no other satellite is similar to Triton since it has a large mass and it is in a highly inclined and retrograde orbit around Neptune. Therefore we explore numerically the stable regions where direct orbits of the spacecraft can survive for different values of inclinations and semi major axes. The effect of the oblateness in the case of Kozai-Lidov is shown. Some Poincaré surfaces of section show the complexity of the solutions for two typical constants of energy.*

Keywords*: Mission, Space Exploration, Orbits, Aerospace Engineering, Neptune-Triton*

1. Introduction

Recently Solórzano et al (2004) proposed a mission to Neptune, analyzing several schemes for the trip Earth to Neptune. In their work the authors were mostly interested in the different strategies to be considered taking into account the compromise between cost and time of flight. In this work we revisit this problem, but our main purpose is to investigate some problems which are connected to the dynamics of the spacecraft, that is, when it is already an orbiter of the Neptune-Triton system.

As mentioned before, since Triton's mass is very significant (2.09E-4 in terms of Neptune´s mass), the orbiter should be strongly disturbed by Triton. Moreover its orbit is very peculiar: highly inclined and retrograde (156.8º). The history about the origin of this curious satellite is very old and there are several theories trying to explain the present scenario. Nowadays Neptune has a family of six small inner satellites (discovered by Voyager). The outermost of this group is Proteus whose semimajor axis is about 4.75 R_N where R_N is Neptune's equatorial radius. Besides these satellites we have Nereid, which is also very peculiar. Its semi major axis is about 222.6 R_N and the eccentricity is 0.75. In spite of this high eccentricity, the mass of this satellite is very small (2 E-07), so that, it barely can disturb a spaceprobe that usually is designed to remain close to the mother planet. There exist others small exterior satellites with almost zero mass, recently discovered (Holmann et al, 2004 and references therein). In the same way, these small objects are not important for our purposes in this work. Therefore we basically consider the system formed by Neptune-Triton and the spaceprobe. As pointed out in Hammel et al (2002), Triton´s surface seems to be very interesting and exhibits a lot of curious features: surface composition, geology, activity, etc, so that high resolution imaging is needed. Therefore, besides the case where the spacecraft orbits Neptune, we also consider some situations where the orbiter is hosted by Triton , while the main disturber is Neptune.

2. Motions around Lagrangean equilibrium points

In this work, the following values were adopted:

R_N=25225 Km (Neptune´ s equatorial radius)
J_2=3410.473591490E-6 (Neptune´ s oblateness coeficient)

For Triton the following notation and values were considered as initial conditions:

a_T=14.325 R_N (semi major axis)
e_T=0.000016 (eccentricity)
I_T= 156.834472º (inclination with respect to the invariable plane)
w_T=0º (argument of the pericenter)
Ω_T=0º (longitude of the node)
λ_T= mean longitude
The same notation is used for the spacecraft omitting the subscript $_T$.

The circular restricted three body problem describes the dynamics of a test particle which moves in the gravitational field of two massive bodies that revolve around their common center of mass. The equations of motion are therefore, most naturally presented in a non-inertial coordinate system that rotates with the mean motion of the primaries. In this coordinate system it is well known that the problem presents two stable equilibrium solutions $L_{4,}$ $L_{5.}$ These are the classical lagrangean equilibrium solutions. Our problem is not exactly equal to the circular restricted three body problem, mostly because we have to consider the oblateness of the mother planet which affects not only the particle but Triton as well. Even so, the lagrangean points $L_{4,}$ $L_{5,}$ still exist (in spite of some small displacement). Therefore in this section we want to explore the motion of the orbiter in the neighbourhood of these points. More precisely, starting from some specific initial values we want to derive the maximum displacement around 60º we can apply in the mean longitude (λ) in order to have the spaceprobe still locked in the libration regime. Our reference system is fixed in the planet and we integrate the usual Newtonian equations.

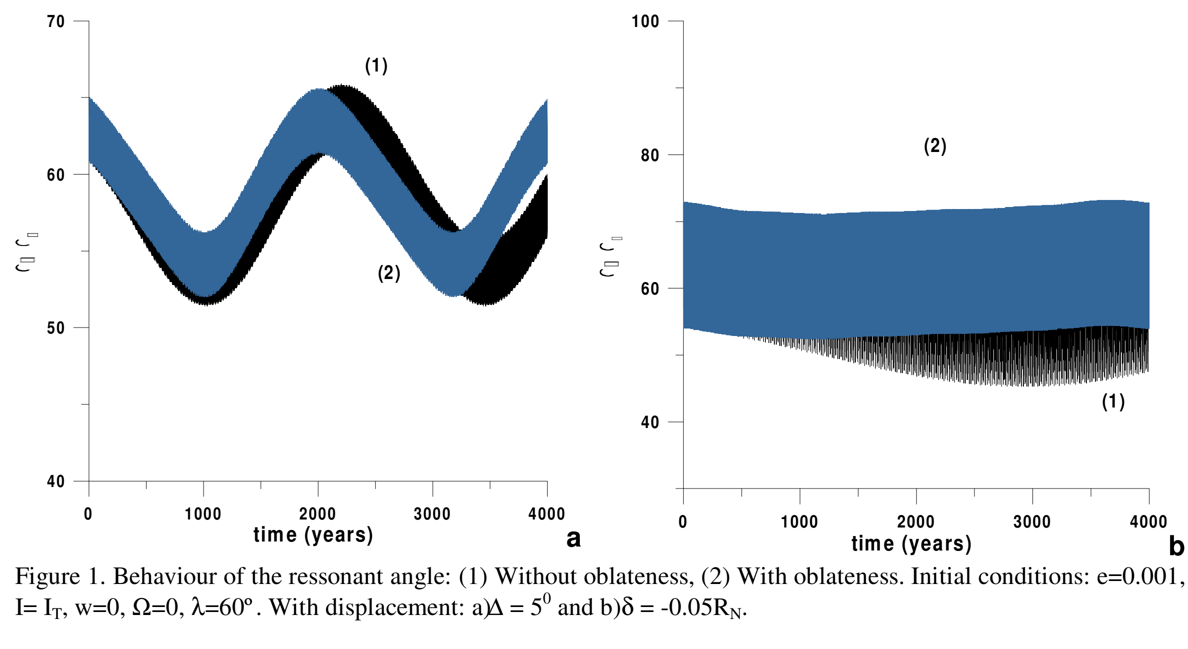

Figure 1. Behaviour of the ressonant angle: (1) Without oblateness, (2) With oblateness. Initial conditions: e=0.001, I= I_T, w=0, Ω=0, λ=60º. With displacement: a)$\Delta = 5^0$ and b)$\delta = -0.05R_N$.

For the initial values we consider w_T=Ω_T=λ_T = 0 and for the satellite, a = a_T, e = 0.001, I = I_T, w = w_T, Ω = Ω_T, λ = 60º+Δ. Figure 1 shows a typical libration of the resonant angle (λ -λ_T) and also the variation of the inclination when the oblateness is considered. In this case, we found Δ = +95^0 and Δ = -42^0, that is, for initial values λ-λ_T larger than 60º+95^0 or less than 60º-42^0 the angle (λ-λ_T) circulates. If J_2 is neglected these values change to : Δ = +98^0 and Δ = -43^0. Some numerical experiments have shown that the corresponding effect of the oblateness seems to be week, specially for the eccentricity. Therefore we do not present the corresponding variations. Figure 1a shows the variations of the ressonant angle for Δ = 5^0.

Let us now investigate the maximum displacement we can apply around a = a_T, such that the libration is still preserved. In all these simulations we take as initial conditions: a = a_T +δ, e = 0.001, I = I_T, w = w_T = 0, Ω = 0, Ω_T = 0 , λ

= 60º, $\lambda_T = 0$. In the case we include J_2 we found $\delta = +0.375R_N$ and $\delta = -0.325R_N$. In Fig. 1b we have the variations of the ressonant angle for $\delta = -0.05R_N$. When J_2 is neglected we find $\delta = +0.375$ and $\delta = -0.325$. As before, numerical experiments show that the inclusion of the oblateness is not significant. The main reason of the weak contribution of J_2 is because, up to now, in all cases we considered orbits not so close to the primary, and the mutual inclination between Triton and the spacecraft were almost zero. In the next section we study some orbits closer to the planet taking different situations where the mutual inclination is important.

3. Motion Close to Neptune

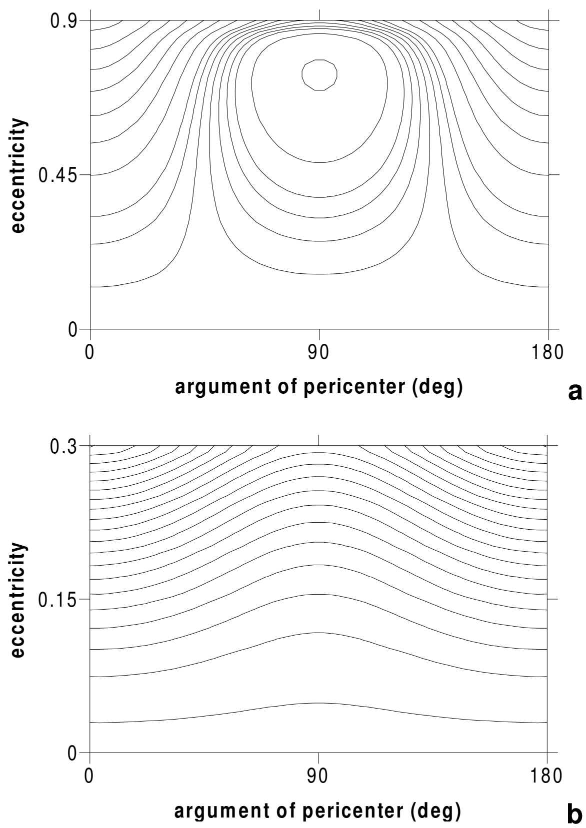

Figure 2. Level curves: eccentricity vs argument of pericenter. when J2=0. a)large variations of the eccentricity in the case of Kozai resonance. b)initial small eccentricity remains almost unchanged in the absence of the stationary point (adapted from Yokoyama et al, 2003).

In this case the effect of the oblateness is very important. Here we want to show some interesting behaviour of the eccentricity of the spacecraft when different inclinations are considered. In the asteroidal motion it is well known that for moderate or high inclination, an asteroid can suffer significant variation in the eccentricity due to the effect of the Kozai-Lidov resonance (Kozai, 1962). For exterior planetary satellites we can show that this kind of resonance occurs when the inclination of the satellite is in the interval 40º - 141º (Yokoyama et al, 2003). More precisely, for inclination in this range we can demonstrate that the system can be reduced to a one degree of freedom problem. We notice that since the satellite is an exterior object, the oblateness perturbation is neglected. Therefore the level curves of the corresponding Hamiltonian show typical trajectories like those given in Figure 2a.

In the first panel, due to the existence of the equilibrium point, we easily conclude that an almost circular orbit can become very eccentric, while in the second, the eccentricity does not suffer significant variation. The situation is similar in our problem: Fig. 3a show a significant variation of the eccentricity of the spaceprobe (full, thick lines), in the case when J_2 is neglected. However when J_2 is included, this large variation almost disappears (dashed lines). The reason is due to the perturbation caused by J_2, which contributes with an additive term in the frequency of the pericenter.

This additive term destroys the previous equilibrium point, so that in the absence of this point, the corresponding trajectories of the second panel in Fig.2b, remains almost parallel to the horizontal axis, because the pericenter w is now circulating instead of librating. The variations of the corresponding pericenter are given in Fig.3b.

Therefore, thanks to the oblateness´ effect , highly inclined orbit can remain very stable. It is worthwhile noticing that without this moderator effect of J_2, the spacecraft can be ejected very easily depending on the inclination. Figure 4a shows an example of escape due to Kozai-Lidov resonance, when the oblateness is neglected. In Fig.4b we have the corresponding variation of the inclination which shows clearly the main feature of this kind of resonance, that is, the maximum of the inclination is attained at the minimum of the eccentricity and vice-versa. In the case when the spacecraft is in 2:1 mean motion resonance with Triton, again J_2 plays an important role, i. e., the effect of this resonance can be drastically enhanced with the inclusion of the oblateness effect. In particular, the case of a mean motion resonance in the retrograde case is slightly different when compared to classical direct cases (Yokoyama et al 2005).

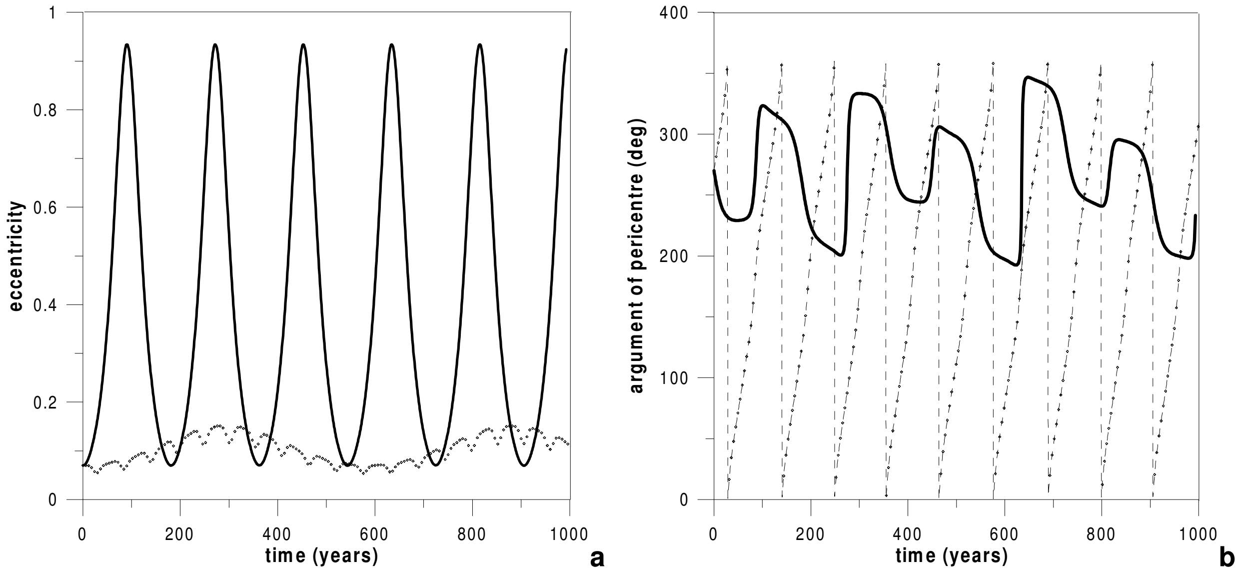

Figure 3. Variations of the eccentricity and pericenter. Initial conditions: e=0.07, I= 49^0, w = 270, Ω=270 , a = $6.5R_N$. Full lines: without J_2 and dashed lines: with J_2.

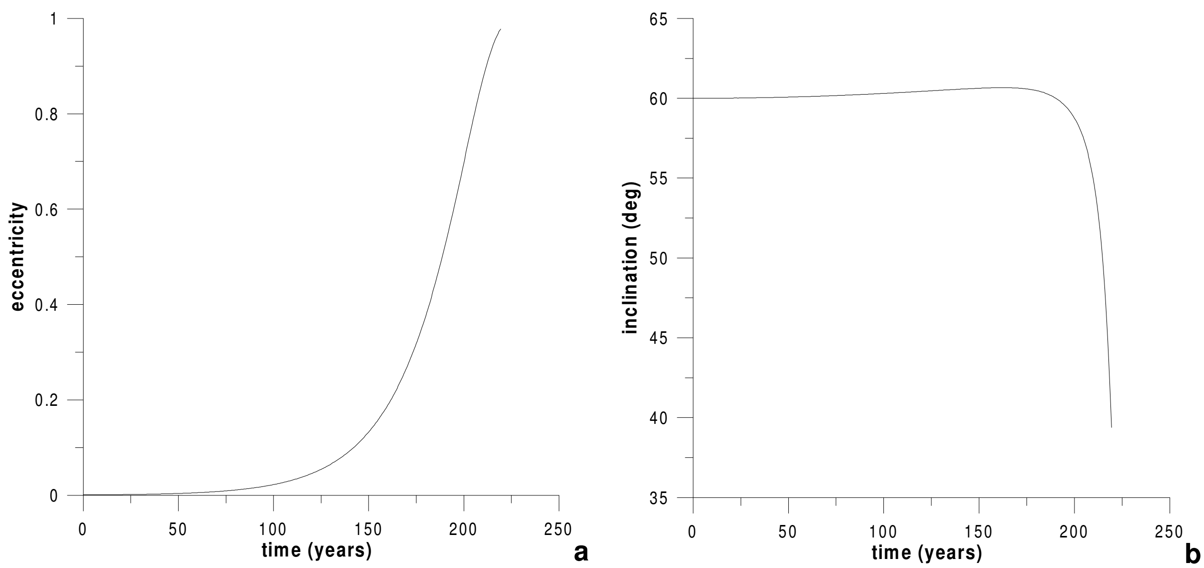

Figure 4. Variations of the eccentricity and inclination. Initial conditions: e=0.01, I= 60^0, w = 0, Ω=270 , a = $6R_N$.

4. Motion Around Triton

As mentioned before, since Triton´ s atmosphere, surface, geology, etc, seems to be a rich source of very important studies, let us investigate, very briefly, the dynamics of the orbiter around this satellite. In this case the main disturber is Neptune. The volume near a planet where satellites are dynamically stable is roughly given by the 'Hill Sphere', within which the planet's gravity overcomes solar perturbations. The radius of the Hill sphere is $R_H = a_p/(\mu/3)^{1/3}$, where a_p is the planet's semimajor axis and μ is the reduced mass.

The numerical integrations of Holmann et al (2004) show that prograde satellites of Neptune are stable to distances of 0.4 R_H and retrograde satellites are stable up to 0.7 R_H depending upon the satellite's eccentricity and inclination. Here we study the orbits of several clones (spacecraft) around Triton, considering the Neptune's oblateness. From the above formula, the Hill sphere is approximately 0.580 Neptune's equatorial radius. In the Earth-Moon problem, the existence of some distant stable orbits of the Moon, was studied by Winter and Vieira Neto (2002). Here we want to study some regions in the neighbourhood of Triton where the spacecraft can remain captured by Triton, taking into account the oblateness of the planet. Since the case of retrograde orbit requires more details, we leave it for a future work. The regions in which we can place the clones around Triton has a strong dependence on the initial eccentricity and inclination. In order to visualize very roughly, the regions where the clones can survive for some interval of time we plot in a two dimensional plane the initial semi major axis and initial inclination (Vieira Neto and Winter, 2001). A color scale associates the time of permanence in the region. Our criterion of escaped orbit means that the clone left or is out of the Hill sphere.

We take the clones in direct orbits, with the initial conditions: $w = \lambda = 0$, $e = 1E\text{-}4$, $\Omega = 90^o = -\Omega_T$. In this work we show only a small region of the (e, I) plane, leaving the remaining part of the scenario to another work. It is interesting to mention the existence of the large stable region in the bottom part of Fig. 5. However since our integration time was fixed to only one thousand years, this region may change if the integration is extended to longer time.

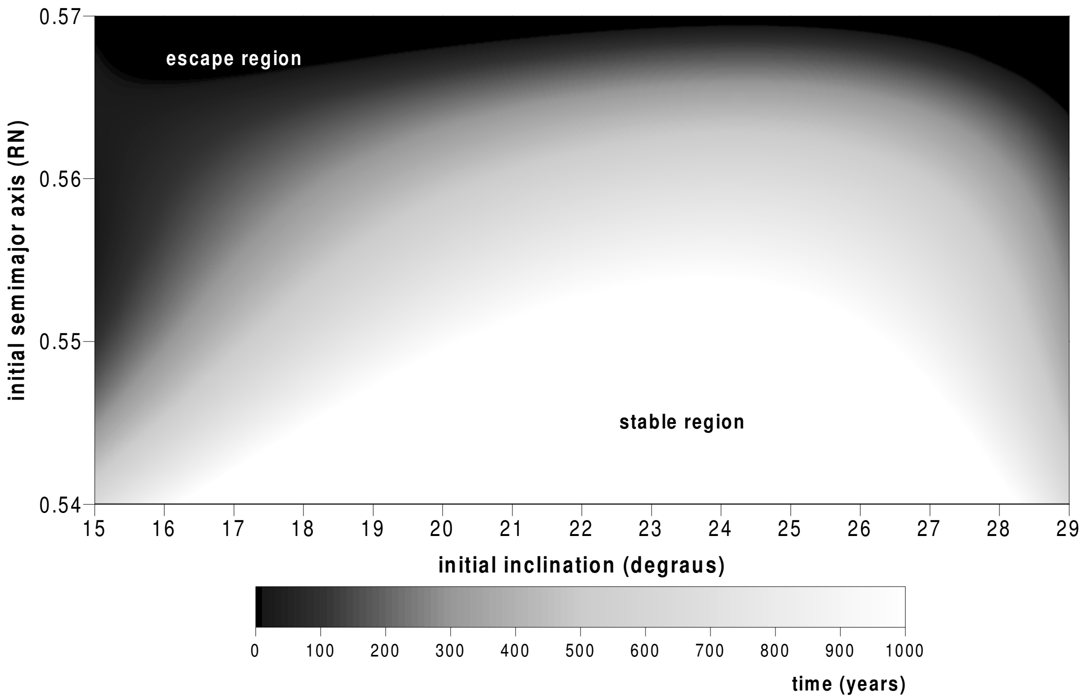

Figure 5. Map of survival time as function of the initial condition.

5.- Poincaré surfaces of section

Strictly speaking, our present system: spacecraft ,Triton and Neptune with its oblateness, is not the classical circular restricted three body, where for the planar case, the Poincaré method of surface section is an excellent tool to examine the general topology of the phase space. With this method, the qualitative dynamics, chaotic and regular regions can be determined very clearly. In our problem, if we assume the particle in the orbital plane of Triton and neglecting the Neptune´ s oblateness we can approximate it to the classical one Of course this is a crude approximation, but even this simplified model serves to show how the solutions can become complex as long as time increases.

In Fig. 6a the Jacobi´ s constant was fixed to C=3.015 (normalized units) and all the points are due toa single orbit starting near to L_1, that is $x_0 = 0.9500$, $(dx/dt)_0 = 0$ In Fig. 6b we adopted C=3.026 and again all the points were generated with a single orbit starting at $x_0 = 0.9080$, $(dx/dt)_0 = 0$. The remaining white regions, not filled with the points represent islands where quasi-periodic orbits can survive. Except in these islands, the motion of the particle is chaotic.

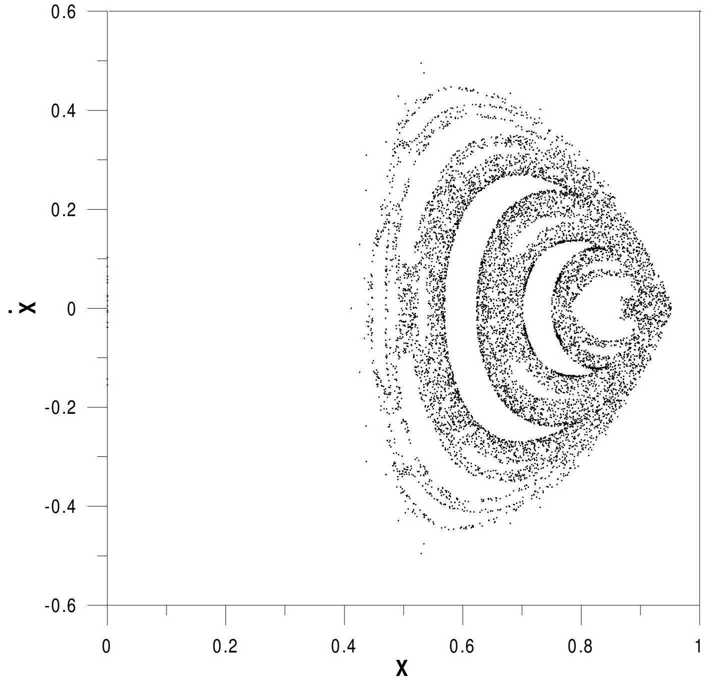

Figure 6a.Poincaré surfaces of section for Jacobi constante: $C_J = 3.015$

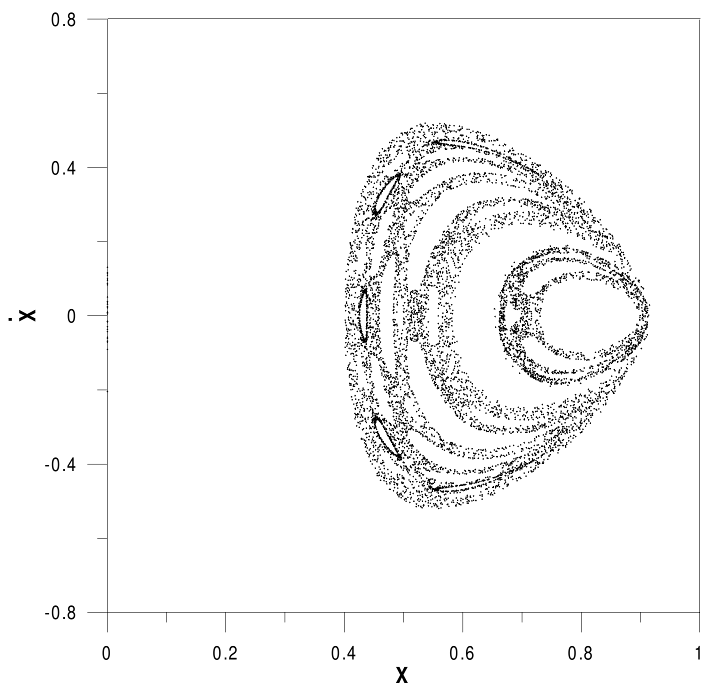

Figure 6b.Poincaré surfaces of section for Jacobi constante: $C_J = 3.026$

6. Acknowledgements: The authors thank FAPESP,CNPQ, CAPES and FUNDUNESP

7. References

Hammel, H. B; et al., 2002, “Exploration of the Neptune System 2003-2013”. The Future of Solar System Exploration, ASP Conference Series. V. 272.

Holman, M.J et al. 2004, “Discovery of five irregular moons of Neptune” , Nature, 430, 865.

Kozai, Y., 1962, "Secular perturbations of Asteroids with High Inclination and Eccentricity", Astronomical Journal, Vol.67, pp. 591-598.

Solórzano, C.R.H.; Sukhanov, A.A.; Prado, AF.B.A., 2004, "Optimization of transfers to Neptune". Presented in 5 th International Conference on Mathematical Problems in Engineering and Aerospace Sciences, Timisoara, Romênia, abstract p.31.

Winter, O.C.; Vieira Neto, E., 2002, "Distant stable direct orbits around the Moon". Astronomy and Astrophysics. Vol.393, pp. 661-671.

Vieira Neto E, Winter O C. 2001, "Time Analysis for Temporary Gravitational Capture: Satellites of Uranus ", Astronomical Journal, Vol.122, p.440.

Yokoyama et al., 2003, "On the orbits of the outer satellites of Jupiter", Astronomy and Astrophysics,Vol.401, pp. 763 - 772.

Yokoyama et al., 2005, "Inner Satellites of Neptune: I The Disturbing Function", Advances in Space Research, in press.

8. Responsibility notice