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Mean motion resonances among the small satellites of Saturn and Pluto

THAMIRIS DE SANTANA

Mean motion resonances among the small satellites of Saturn and Pluto

Thesis submitted to the School of Engineering of Guaratinguetá, São Paulo State University, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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For all women before me, with me and after me.

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Sometimes science is more art than science.
(Rick Sanchez)

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Abstract

This work is organized into three parts. In Part I, we present a quick review of Saturn's satellites Prometheus and Pandora lags problem. We analyzed the lags ratio $\left(\mathcal{Q} = \left|\frac{\Delta\lambda_{\rm pro}}{\Delta\lambda_{\rm pan}}\right|\right)$ through the conservation of the angular momentum, that implies the ratio of the lags due to this mutual interaction must be almost constant. However, we found that the values obtained using observational data fit $\mathcal{Q}_{\rm obs}$ does not agree with the assumed masses $m_{\rm pan}/m_{\rm pro} = 0.56$ and is not even nearly constant. It presents a robust linear increasing rate given by $\mathcal{Q}_{\rm obs}(t) = 0.667 + 0.013t$, with t given in years. In this way, we show that only the gravitational interaction between the satellites does not fully explain the lags values. This indicates that a non-mutual mechanism should provoke at least a mean motion changing of 0.45°/year, also affecting Prometheus or Pandora, contributes to the lag values.

In Part II, we performed the astrometry of the satellite Daphnis using the CAVIAR software in a selected set of images from the ISS-NAC camera of Cassini spacecraft. Daphnis' astrometry of all Cassini mission period showed that Daphnis had changed its orbit twice. So, we have investigated the stability of Daphnis' orbit by implemented numerical simulations considering Saturn plus five satellites: Daphnis, Atlas, Prometheus, Pandora, and Mimas and computing the evolution of the Fast Lyapunov Indicator FLI. We showed that Daphnis is on a chaotic orbit with a Lyapunov time of ∼13 years. By investigating possible resonances between Daphnis and other satellites, we found that Prometheus and Atlas with 129:125 and 157:155 mean motion resonant angles, respectively, present some features that could indicate chaos. Additionally, we found that when Prometheus and Atlas are not included in the numerical simulation, Daphnis' orbit became regular, reinforcing the suggestion that both satellites are playing a role in Daphnis' chaotic behavior.

In Part III, we presented a study of the origin of resonance between the satellites of Pluto. We performed N-body numerical simulations considering the small satellites and Charon evolving under the influence of the tidal force due of Pluto on Charon. Using the J_2 *effective* approach, we showed that the small satellites could be captured into the 3:1, 4:1, 5:1, 6:1 mean motion resonances with Charon. Even for the case of the 5:1 and 6:1 mean motion resonances, it was possible to achieve a capture only when some non-zero eccentricity was added to Charon. Moreover, the 3:1 mean motion resonance between Charon and Styx, in inclination, was the easiest to happen. To find the three body resonance 3:5:2 among Styx, Nix, and Hydra, we looked for two particular resonances among them: 2:1 between Styx and Hydra and 5:4 between Nix and Styx. We have found parameters that allow the capture of the small bodies into the exact two 2-body resonant arguments we need, but not at the same time. In this way, we perceive that we are close to finding the right parameters to represent all the paths of the Pluto's moons from their past to the current intriguing configuration. Some different ideas may be tested to bring us to the present scenario.

Keywords: Resonances, satellites, Saturn, Pluto.

SANTANA, T. **Ressonâncias de movimento médio entre pequenos satélites de Saturno e Plutão.**. 2019. 103 p. Tese (Doutorado em Física) - Faculdade de Engenharia do Campus de Guaratinguetá, Universidade Estadual Paulista, Guaratinguetá, 2019.

Resumo

Este trabalho está dividido em três partes.

Na Parte I é apresentada uma breve revisão sobre o problema da defasagem dos satélites Prometeu e Pandora de Saturno. Analisamos a razão entre as defasagens $\left(\mathcal{Q} = \left|\frac{\Delta\lambda_{\mathrm{pro}}}{\Delta\lambda_{\mathrm{pan}}}\right|\right)$ através da conservação do momento angular, o que implica que o fator $\mathcal{Q}$ devido à perturbação deve ser praticamente constante. Contudo, verificou-se que os valores ajustados a partir de dados observacionais $\mathcal{Q}_{\mathrm{obs}}$ não está de acordo com a razão de massas assumidas $m_{\mathrm{pan}}/m_{\mathrm{pro}} = 0.56$ e também não tem um comportamento constante. Verificou-se que há um aumento linear dado por $\mathcal{Q}_{\mathrm{obs}}(t) = 0.667 + 0.013t$, com t dado em anos. Desta forma mostrou-se que somente a interação gravitacional entre os satélites não explica completamente os valores das defasagens. Isso indica que algum mecanismo não-mútuo deve causar pelo menos uma alteração no movimento médio de 0.45°/ano de Prometeu ou Pandora e contribui para os valores das defasagens.

Na Parte II é realizada a astrometria do satélite Daphnis utilizando o software CAVIAR para um conjunto selecionado de imagens da câmera ISS-NAC da sonda Cassini. A astrometria do satélite para todo o período da missão Cassini mostrou que Daphnis mudou sua órbita duas vezes. Assim, foi investigada a estabilidade orbital de Daphnis através de simulações numéricas considerando Saturno e cinco satélites (Daphnis, Atlas, Prometeu, Pandora e Mimas) e calculando a evolução do Indicador Rápido de Lyapunov. É mostrado que Daphnis está em uma órbita caótica com um tempo de Lyapunov de ∼22 anos. Investigando possíveis ressonâncias entre Daphnis e outros satélites, verificou-se que as ressonâncias 129:125 e 157:155 com Prometeu e Atlas, respectivamente, apresentam algumas características que podem indicar caos. Adicionalmente, em simulações numéricas sem os satélites Prometeu e Atlas a órbita de Daphnis permaneceu regular, reforçando a idéia que são estes dois satélites que tem um papel relevante no comportamento caótico de Daphnis.

Na Parte III é apresentado um estudo da origem das ressonâncias entre os satélites de Plutão. Foram realizadas simulações numéricas do problema de N-corpos considerando os pequenos satélites e Caronte, incluindo a migração de Caronte devido à força de maré. Utilizando a abordagem do J_2 *efetivo* mostrou-se que os pequenos satélites podem ser capturados nas ressonâncias de movimento médio 3:1, 4:1, 5:1, 6:1 com Caronte. Para os casos das ressonâncias 5:1 e 6:1 foi possível obter uma captura somente quando uma excentricidade não nula foi considerada para Caronte. Além disso, a ressonância de movimento médio 3:1 em inclinação entre Caronte e Estige é a mais fácil de ocorrer. Para encontrar a ressonância de três corpos 3:5:2 entre Estige, Nix e Hidra procurou-se por duas ressonâncias específicas entre os satélites: 2:1 entre Estige e Hidra, e 5:4 entre Nix e Estige. Foram encontrados parâmetros que permitem a captura dos pequenos satélites exatamente com os argumentos das ressonâncias de dois corpos necessárias, porém não simultaneamente. Desta forma, sabe-se que é um caminho promissor para determinação dos parâmetros para representar a evolução dos satélites de Plutão até suas posições atuais.

Palavras-chave: Ressonâncias, satélites, Saturno, Plutão.

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Chapter 1

Introduction

In this work, we present three different dynamic systems of small bodies under the influence of mean motion resonances.

The text is divided into three independent parts. In Part I, we present a quick review of Saturn's satellites Prometheus and Pandora lags problem, defined by the difference in their angular positions found fifteen years after their discovery. In Chapter 2, we present a bibliographical review of the works on this topic. In Chapter 3, we show the implications of the conservation of angular momentum on this system, and we show the ratio between the lags will be nearly constant and inversely proportional to the ratio of their masses. Chapter 4 is devoted to the discussion of the evolution of the ratio between the lags, and later it is presented a brief discussion on the satellites mass ratio related to those values. We highlight some known interaction with Prometheus or with Pandora that could be causing the anomaly found, and the final comments on this part are presented.

In Part II, we show a study regarding the Daphnis satellite, starting from the analysis of its images taken by Cassini to its orbit. In Chapter 5, we introduce the satellite and its discovery by Cassini. Chapter 6 presents the process to make the astrometry of Daphnis using CAVIAR. By using images from 2004 to 2014, it is shown that Daphnis has changed its orbit. So, in Chapter 7 Fast Lyapunov Indicator (FLI) is presented, by performing numerical simulations we investigate the stability of Daphnis orbit, and we show its chaotic movement. Moreover, we investigate if there are any moons related to Daphnis chaotic behavior and analyzing mean motion resonances. It also contains the final comments on this part.

Finally, in Part III, we present a study of the origin of the resonance between the satellites of Pluto. In Chapter 8, we describe the system and its particular configuration. Chapter 9 presents our methodology and how we proceed to take Charon's presence into account to analyze the small satellites orbits. In Chapter 10, we show the numerical simulations, analyze the results and it contains the final comments on this part.

Chapter 11 summarizes all the three parts of the work, highlighting the main results.

Chapter 11

Final Remarks

In this work, we have passed through different studies involving the mean motion resonances of small satellites.

In Part I we presented a quick review on Saturn's satellites Prometheus and Pandora lags problem and analyzed the ratio between them ($\mathcal{Q} = \left|\Delta\lambda_{\rm pro}/\Delta\lambda_{\rm pan}\right|$). The 121:118 mean motion resonance between Prometheus and Pandora is the explanation proposed by Goldreich & Rappaport (2003b) for the lags. Through the conservation of the angular momentum, we expect that the ratio of the lags due to this mutual interaction must be almost constant. However, the values obtained using observational data fit French et al. (2003), $\mathcal{Q}_{\rm obs}$ does not agree with the assumed masses $m_{\rm pan}/m_{\rm pro} = 0.56$ and is not even nearly constant. It presents a robust linear increasing rate given by $\mathcal{Q}_{\rm obs}(t) = 0.667 + 0.013t$, with t given in years. In this way, we show that only the gravitational interaction between the satellites does not fully explain the lags values, indicating that a non-mutual mechanism should provoke at least a mean motion changing of $0.45°$/year, also affecting Prometheus or Pandora, contributes to the lag values. We have listed a set of known gravitational interactions involving Prometheus or Pandora.

In Part II, we performed the astrometry of the satellite Daphnis using the Caviar software in a selected set of images from the ISS-NAC camera of Cassini spacecraft. The results indicated that only one orbit does not describe Daphnis positions during the years of the Cassini mission. Instead, it changed through three different orbits, implying Daphnis has been unpredictably changing orbit. So, we have investigated if Daphnis is orbiting in a stable region, and for this, we implemented numerical simulations considering Saturn plus five satellites: Daphnis, Atlas, Prometheus, Pandora, and Mimas. By computing the evolution of the Fast Lyapunov Indicator FLI over time for Daphnis orbit, we showed that the moon is on a chaotic orbit with a Lyapunov time of $\sim$22 years. It is a short Lyapunov time, implying that Daphnis is within a highly chaotic region. Thereafter, we investigated the existence of some possible resonances between Daphnis and other moons that could be relevant for Daphnis' orbital motion. It was found that Prometheus and Atlas and 129:125 and 157:155 mean motion resonant angles present some features that could indicate chaos. Later, we found that when Prometheus and Atlas are not included in the numerical simulation, Daphnis' orbit became regular, reinforcing the suggestion that both satellites are playing a role in Daphnis' chaotic behavior.

In Part III, we presented a study of the origin of resonance between the satellites of Pluto.

We performed N-body numerical simulations considering the small satellites and Charon at initial semimajor axes closer to Pluto than their current positions and evolved the system in time under the influence of the tidal force due to Pluto-Charon. Using the J_2 *effective*, we were able to calculate a set of orbital elements instantly on time from the output state vector from the simulation by considering a central object as a single oblate body with a radius of 1187 km and a mass equivalent to the sum of the masses of Pluto and Charon. We showed that the small satellites can be captured into the 3:1, 4:1, 5:1, 6:1 mean motion resonances with Charon. For the case of the 5:1 and 6:1 mean motion resonances, it was possible to achieve a capture only when some artificial eccentricity was added to Charon. Moreover, the 3:1 mean motion resonance between Charon and Styx, in inclination, was the easiest to happen. To find the three body resonance 3:5:2 among Styx, Nix, and Hydra, we looked for two particular resonances among them: 2:1 between Styx and Hydra and 5:4 between Nix and Styx. For several simulations, it was found only one resonance between Styx and Hydra, and not those we need to form the three bodies one.

Then, to find other constraints on the captures into resonances among the small satellites, besides, the use of the J_2 *effective* simulations' output, we also adopted the J_2 *effective* approximation idea through all the evolution. In other words, instead of having Charon present during the simulation, we suppressed it and replaced Pluto for a body with Pluto and Charon masses and a J_2 coefficient, as we have said earlier. Also, we used an artificial force to damp the orbital's eccentricity of the moons captured and have changed the initial semimajor axes of them in order to allow the 5:4 and 2:1 mean motion to happen simultaneously. Unfortunately, it turned out to be harder than we expected.

Summarizing, we have parameters that allow the capture of the small bodies into the exact two 2-body resonant arguments we need, but not at the same time. On the other hand, we have other parameters that allow the capture at the same time as the resonances we want, but not for the arguments we need.

The magnitude of the tidal force, the magnitude of the drag force, and the initial position of all moons are the variables of this problem, making it hard to suit all those simultaneously. That is why we had passed through each mechanism individually, trying to identify in what conditions such things can happen.

In this way, we perceive that we are close to find the right parameters to represent all the paths of the Pluto's moons from their past to the current intriguing configuration.

Some different ideas may be tested to bring us to the present scenario. Some of these ideas are applying a damping eccentricity force on Nix and allowing the captures to happen a little bit earlier or later, provoking a bigger or smaller eccentricity on the small satellites that will allow the capture to happen when the body passes through the resonance location.

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