Dynamical Study on the Formation of the Jovian Irregular Satellites

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Abstract

The dynamical history of the solar system (SS) is described by the Nice Model and its variations, where interactions between the giant planets (GPs) and the primordial planetesimal disc sculpted the dynamical structure that we observe today. However, some dynamical classes of objects - such as the irregular satellites of the GPs - still need better explanation about their origin mainly due to new observational discoveries and evidences. This population is believed to be captured from different families and groups during the evolutional history of the SS. Therefore studying this class of objects can provide important restrictions to the models used to simulate the formation of our planetary system.

Numerical simulations present good agreement between the number of predicted and observed irregular satellites for the outer giants (Uranus and Neptune). On the other hand, specially for the case of Jupiter, it is still lacking a better understanding of the capture mechanisms. Nesvorný et al. 2007 and 2014 studied those mechanisms and evolution of the jovian irregular satellites using N-bodies numerical simulations in the context of the Nice Model and the Jumping Jupiter.

Abstract

Here we present the results of recent simulations where we first followed similar procedures as used by Izidoro et al. 2015 and 2017 – and references within – on which we implemented the gas density profile, temperature gradient, and torques on the gas suffered by a planet with Type I migration, and act under the effects of the thermal and viscous diffusion of the gas. We also included damping effects on eccentricities and inclinations and accelerations, besides the equations for migration time scale.

In our work we first performed comparative tests for code validation and thousands of simulations using different initial conditions such as: number of planetary embryos (super-Earth); total mass of planetary embryos; initial orbital parameters (a,e,i,f,ω,Ω). Then we selected the best case scenarios where it was formed Uranus and Neptune and analysed the close encounters that happened between the GPs.

Introduction

In 2007, using the Nice Model, Nesvorný et al presented a study on the capture of irregular satellites during planetary encounters occurred during the period of instability of the SS, when Jupiter and Saturn interact after crossing the 2:1 mean motion resonance (MMR). On their work they find that the probability of capture is enough for the external giant planets but is smaller than expected for Jupiter. This was mainly due to low interactions and close encounters with other GPs during the evolution of the system.

In 2014, the authors now performed a similar study now using the Jumping Jupiter model. When including a 5th GP the number of close encounters with Jupiter increases and, consequently, the probability of capturing irregular satellites, but they are still unsatisfactory. More recent studies on the formation of the SS, such as the ones by Izidoro et al. 2015 and 2017, include a few super-Earth on the simulations, which will increase the number of close encounters with Jupiter, when immersed in a primordial planetesimal disc and the presence of gas.

Using a similar procedure, we intend to obtain a similar capture probability for irregular satellite that is more consistent with the current number of satellites we know to date.

Methodology

In this context, we use a scenario where Jupiter and Saturn are already formed, starting with semimajor axis close to the 5:2 mean motion resonance (MMR) and immersed in a gaseous protoplanetary disc. The gas density profile is interpolated from hydrodynamic simulations where Jupiter opens a deep gap on the disc and migrates with type-II migration. Besides that, super-Earths (with masses of 5 to 10 Earth masses) are included and distributed in initially circular and coplanar (to the gas disc up to 10 au) orbits. The evolution and migration of those planetary embryos are studied in order to check possible close encounters with Jupiter, and the formation of Uranus and Neptune. We the use similar metrics from Nesvorný et al. 2014 to compare the simulated and real population of jovian irregular satellites.

The following step will be to select the best case scenarios and run the simulations now considering the planetesimals as binaries. We expect to obtain a formation scenario for Uranus and Neptune that can provide a number of mechanisms that favour the capture of planetesimals by Jupiter that better represents the observed number of irregular satellites. Then we intend to analyse if during the angular momentum exchange there are collisions between the captured binaries, giving some clues on the formation of satellites families, such as Himalia's.

Scenario

Our work uses a similar methodology as presented by Izidoro et al. 2015 and 2017, with N-body numerical simulations to study the dynamical evolution of multiple proto-planets (with Jupiter, Saturn, and a few super-Earths). We include the effects of a gaseous protoplanetary disc with surface density modeled in one dimension (radial direction), as presented in Figure 1.

We also include effects of the gas on the planets and the interaction between the disc and the planet with type-I migration, also considering the eccentricity and inclination dumping, and the torques suffered by the planet as presented by Paardekooper et al. 2010 and 2011. As initial condition, we put Jupiter and Saturn close to the MMR 5:2, with semimajor axis a=5 and 6.2, respectively, and a variety of super-Earths external to Saturn's orbit.

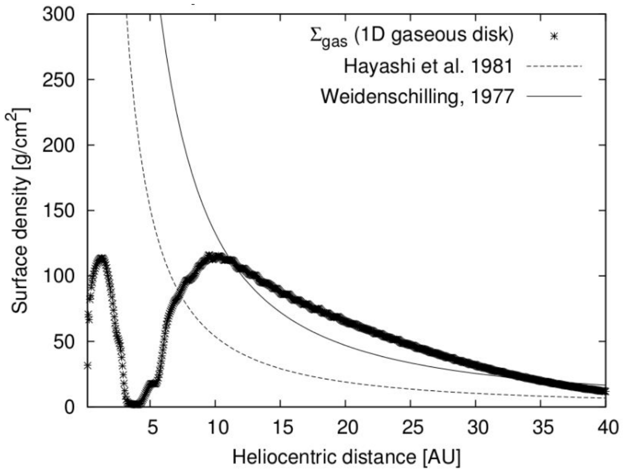

Figure 1: Gas surface density profile - Reproduced from Izidoro et al. 2015.

Results

This work is still in its initial phase. Following the procedures presented by Izidoro et al. 2015 and 2017* - and references therein - we implemented the N-body numerical simulations code (Rebound) using the equations for the gas density profile (x), temperature gradient (β), and gas torques for a planet with type-I migration (Γ_{Tot}) – which include contributions from Lindblad (Γ_L), and co-rotational (Γ_C) torques – that act under the effects from viscous and thermal diffusion of the gas. it was also included the eccentricity and inclination dumping effects (and accelerations), besides equations for migration timescale. Using this code, we performed a few runs to analyze and compare the effects obtained in order to validate the code. Figure 2 present one of the result from a numerical simulation with Jupiter, Saturn and 4 super-Earths.

Results

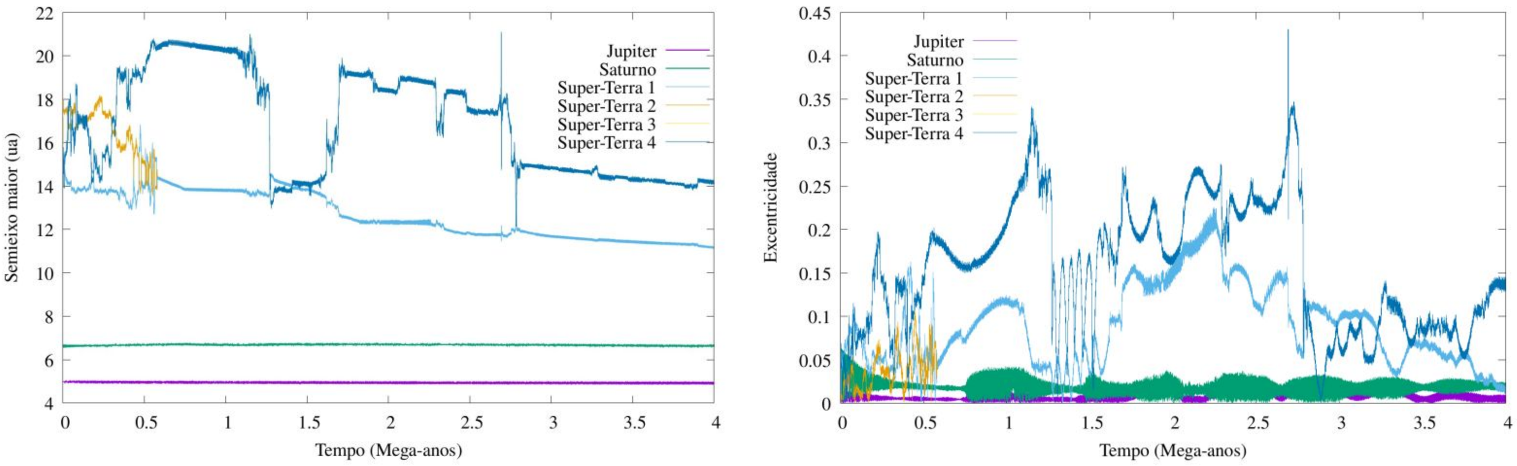

Figure 2: Example of a numerical simulation for 4 Myr, including 6 giant planets (Jupiter, Saturn and 4 super-Earths). Here we present the variation of the semimajor axis (left) and eccentricity (right). Note that there are 2 encounters with merge between the super-Earths.

Next Steps

Using the implemented, tested, and verified code, we now intend to run several numerical simulations in order to obtain the best case scenarios for the formation of Uranus and Neptune. Those cases will be selected to analyze the close encounters between the super-Earths (or GPs) with Jupiter so we can reproduce and improve the capture statistics for the jovian irregular satellites obtained by Nesvorný et al. 2007 and 2014.

On the next step, we will check those close encounters when we consider the planetesimals as binaries and study the captures by Jupiter, in order to explain the jovian irregular satellite formation and families.

References e Acknowledgements

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