# Abstract

The large number of detected giant exoplanets has opened the possibility of improving our understanding of these fascinating objects. The core accretion model is the widely accepted scenario for the formation of exoplanets. In this model, planetary growth begins with the accretion of solids, followed by a buildup of a gaseous atmosphere as more solids are accreted; finally the rapid accretion of gas occurs. In the early core accretion simulations, it was assumed for the sake of numerical simplicity, that all the heavy elements reach the core, whereas the envelope is composed of Hydrogen and Helium (H-He). However, recent numerical simulations indicate that when the core mass reaches a value of 1 - 2 $M_{\oplus}$ solids can fully dissolve into the envelope. Until now, heavy-element enrichment has often been neglected or not modeled self-consistently. This is due to the numerical challenges linked to this problem: in particular, at each time-step it is necessary to compute the deposited heavy-element mass and energy. In turn, the presence of heavy elements in the envelope must be included in the opacity and Equation of State (EOS) calculation to compute the envelope's structure correctly It is important to consider the dissolution of the accreted solids into the planetary envelope for several reasons: first, the presence of heavy elements significantly affect planet growth; second, a non-homogenous internal structure has a significant impact on the thermal evolution and final structure of the planets; finally, the dissolution of the accreted solids offer a link between the formation and present-day internal structure models of Jupiter and Saturn.

In this thesis, I present a new numerical framework to model the formation of giant planets, considering heavy-element enrichment, showing several applications and findings. At each time-step during the formation of the planet, I compute where the accreted solids deposit their mass and energy and I include the presence of the heavy elements in the envelope's microphysics. Such a numerical tool opens up interesting possibilities in planet formation theories due to its large applicability to several unsolved problems.

**First,** I simulate the interaction of planetesimals with a growing giant planet (proto-Jupiter) and investigate how different treatments of the planetesimal-envelope interaction affect the heavy-element distribution and inferred core mass. I consider various planetesimal sizes and compositions, as well as different ablation and radiation efficiencies and fragmentation models. I find that in most cases, the core reaches a maximum mass of $\sim 2\ M_{\oplus}$.

**Second,** I present the numerical framework to model the formation and evolution of giant planets. The code is based on an extension of the stellar evolution toolkit, Modules for Experiments in Stellar Astrophysics (MESA). The model includes the dissolution of the accreted planetesimals/pebbles, which are assumed to be made of water, in the planetary gaseous envelope and it also computes the effect of envelope enrichment on the planetary growth and internal structure self-consistently. I apply the simulations to Jupiter and investigate the impact of different heavy-element and gas accretion rates on its formation history. It is confirmed that heavy-element enrichment leads to shorter formation timescales due to more efficient gas accretion. I find that with heavy-element enrichment, Jupiter's formation timescale is compatible with the lifetimes of typical disks, even when assuming a low heavy-element accretion rate i.e., an oligarchic regime. Finally, I provide an approximation for the heavy-element profile in the innermost part of the planet, providing a link between the internal structure and the planetary growth history.

**Third,** I use the developed numerical tool to simulate the *in-situ* formation of Uranus and Neptune via pebble accretion, showing that both planets can form within a few Myr at their current locations and end up with heavy-element to H-He ratios that are consistent with those predicted by structure models. In many cases, a few earth masses of heavy elements are missing, suggesting that Uranus and/or Neptune may have accreted $\sim 1 - 3\ M_{\oplus}$ of heavy elements via giant impacts. The formation of Uranus/Neptune-mass planets is a natural outcome of planet formation, which is consistent with the large number of intermediate-mass exoplanets detected in the galaxy.

**Finally,** I present an approximation for the capture radius that can be implemented in N-body code in order to improve predictions for the solid accretion rate of planetesimals, which is the key driver in the formation

of giant planets.

I am proud to consider this thesis as an additional step towards developing a better understanding of how fascinating objects such as giant planets are formed.