On the origin of the moons of Jupiter

MSc Thesis

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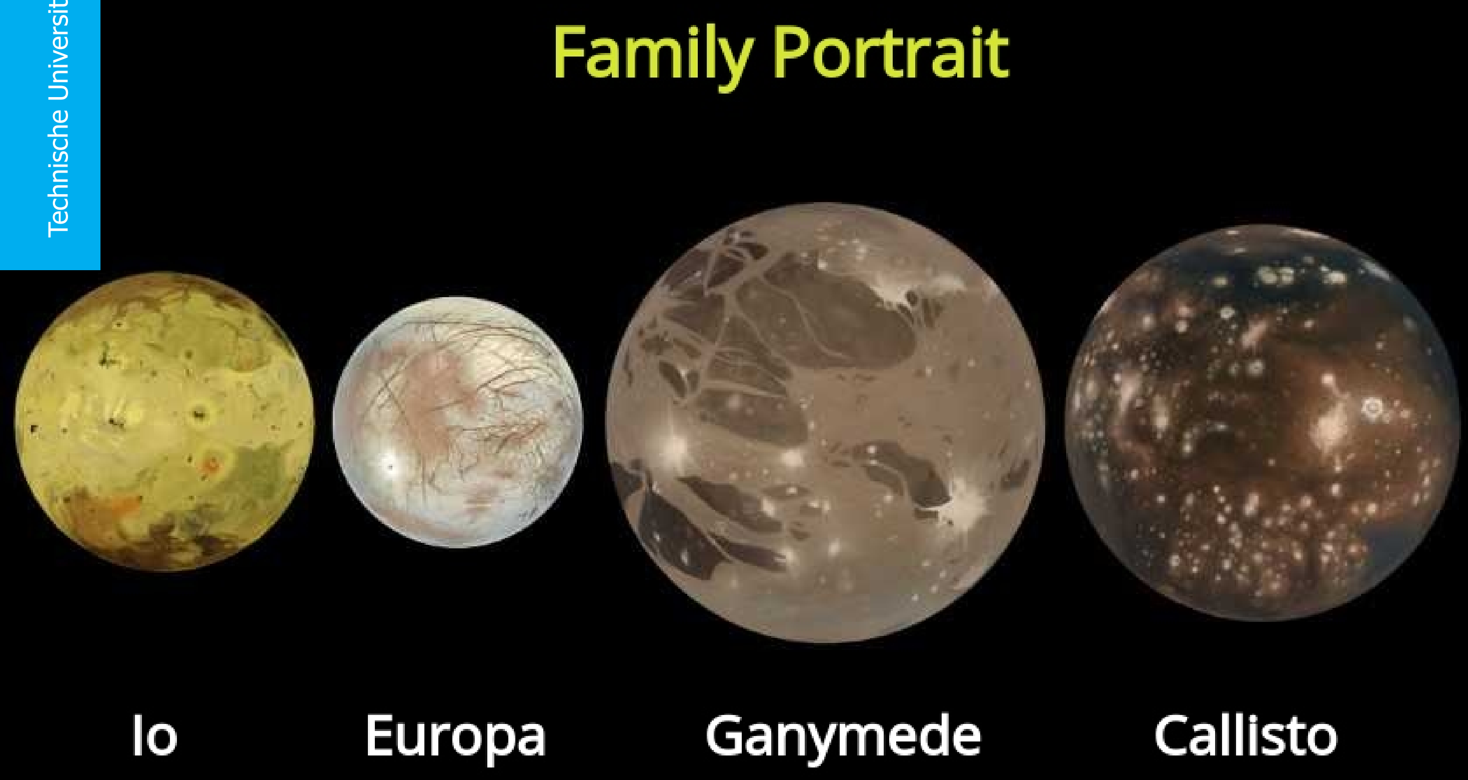

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Challenge the future

On the origin of the moons of Jupiter

by

Matteo Serman

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Abstract

Context: The origin of the Galilean moons of Jupiter has been studied and modelled by a vast range of scientists. It is generally accepted that they formed in a *circumplanetary disk* (CPD), a disk that surrounded Jupiter and from which the moons originated, in a similar fashion to the planets' formation within a *protoplanetary disk* (PPD). However, the theories about the Jovian CPD often present different, if not contrasting, approaches and characteristics; there is still no consensus within the scientific community on this fascinating but difficult topic. What was the CPD mass? How much did the PPD influence the CPD? How much did the young Sun and Jupiter affect the formation? These and many other questions are still open and it will be attempted to give some insights to some of them.

Aims: It is attempted to better define and characterize the formation process and environment of the Galilean moons. Many parameters of the Jovian CPD are still unknown or uncertain. In the simulations performed during this project, many different scenarios will be investigated. These are, for example, the mass of the CPD or the energy emitted by the young Jupiter. The idea is to produce models confirming or confuting existing theories and to deliver the expected ice compositions of the moons if they formed at their current location, which could be confirmed by future missions (JUICE, Europa Clipper) or observations (JWST).

Methods: The bulk of the project are the thermo-chemical simulations conducted with ProDiMo, a specific software designed to model PPDs around stars. In this thesis, for the first time it is applied to a CPD. Being a PPD way larger and relatively "independent", it is a challenge to adapt ProDiMo to the smaller CPD. The effects of the parent disk must be taken into account. The software requires a long list of inputs, which have to be determined. The outputs will then be analyzed with a specifically designed Python tool, called *prodimpopy*.

Results: Many interesting details have emerged. The dominating source of the Jovian CPD seems to be the young Jupiter, which was probably still accreting, since a very bright planet is needed in order to have the water snowline in the proximity of Europa, which is the current leading theory capable of explaining the different ice/rock ratios of the moons. Many more characteristics have been tested and discussed: (1) the young Sun affected mostly the outer regions of the CPD (2) the viscous heating plays an increasing effect as the mass of the CPD decreases (3) the migration of the planets would have disturbed the moons' formation (4) different CPD's mass can still be compatible.

Conclusions: ProDiMo has proven to be able to simulate CPDs. The disk compositions resulting from the several scenarios can be used to test different hypotheses. In this thesis, ProDiMo delivered coherent results with the current theories and numerical simulations, including different CPD masses models and other variables. It however presents certain limitations, like the difficulty to simulate the young Sun, due to the different scope for which it was designed. Solving them would be a great benefit for the research on the origin of the moons.

Acknowledgments

These past seven (nine, ten) months have been a very challenging period of my life. The Master thesis project, the last of an uncountable number of university assignments, the most important one. Many people yelled "wow" when they asked me for my thesis topic - it is not a stereotypical thing you would hear from an aerospace engineering student. But, still, astronomy is fascinating. Many people enjoy staring at the sky, wondering how many galaxies, stars, planets and moons are out there. And I am one of those. Hence, when it was time to start the project, 'the origin of the moons of Jupiter' was immediately noticeable among many other possibilities. I decided to come back to the gold epoch when, during the high school, I was having fun during the International Astronomy Olympiad. And, who knows, maybe my 'astronomization' will utterly continue with a PhD project...

But, this work would have not been possible without the help of many people. First of all, my supervisor and mentor, Stéphanie Cazaux. Merci bien, for offering me this project, for the constant, enormous and invaluable support during the research, during our meetings and via e-mail. For keeping me on the right track, while fantasy or laziness were trying to overcome. Merci, vraiment.

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This research has made use of NASA's Astrophysics Data System, so thanks goes also to this fantastic collection of papers where you can find *anything* astrophysically related.

Also many thanks go to all the people I have had the luck to meet in Delft. You have all contributed to this goal, and I must admit that I am ~~a bit~~ sad to leave this amazing and friendly city. Tanti ringraziamenti anche al mio grande amico Dario, che anche se conosco da nemmeno due anni mi sembra che siano almeno venti. A Giuseppe, grande ballerino e amico, che mi ha fatto tanta compagnia e tante ottime cene. To Sunayna, a very special girl who cooks delicious Indian food and is one of the most friendly person I have ever met. To Dani, Marton and David, my favourite teammates for all the group assignments handed at TU Delft. To all the others who have shared (or maybe are still sharing) the toughness of the Master degree.

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Par finir, come se dize da noaltri, un arbołe no'l połe cresar ben sa no'l gà profonde raize. E łora, tanti tanti grasie va anca a ła me fameja: mama, papà e fradeł. Vialtri si senpre stà i me primi fans, cuełi che i gà senpre credùo in mi, anca cuando łe robe łe pareva nar mał o łe zera difisiłi. Senpre me gavì jutà, e senpre ve dirò grasie, anca sa no'l sarà mai bastansa. A gò fato de'l me mejo par rendarve fieri, spero de esarghe riusìo almanco un pocheto. Grasie de cor, par tuto.

I would like to conclude with one of the most important sentence of the marvellous people to which I have the honour to belong, the Venetians. It is short, but full of meanings and importance for us:
Par tera, par mar, San Marco!

Matteo Serman
Delft, The Netherlands, January 2019

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List of Symbols

- M_J : Mass of Jupiter ($1.898 \cdot 10^{27}$ kg)
- $M_\odot$: Mass of the Sun ($1.988 \cdot 10^{30}$ kg)
- R_J : Radius of Jupiter (69911 km)
- pc : Parsec (3.26 light-years)
- $L_\odot$: Luminosity of the Sun ($3.828 \cdot 10^{26}$ W)
- Myr : Million year (10^6 yr)
- M_E : Mass of the Earth ($5.972 \cdot 10^{24}$ kg)
- AU : Astronomical Unit ($1.496 \cdot 10^8$ km)
- GPa : Giga Pascal (10^9 Pa)

List of Abbreviations

- ProDiMo : Protoplanetary Disk Model
- SED : Spectral Energy Distribution
- PAH : Polycyclic Aromatic Hydrocarbon
- CPD : Circumplanetary Disk
- PPD : Protoplanetary Disk
- ISM : InterStellar Medium
- MMSN : Minimum Mass Sub-Nebula
- JWST : James Webb Space Telescope

1

Introduction

This chapter will give an introduction to the theory and literature sitting behind this thesis. It will start with a description of the Jovian environment, including the works carried out so far in the attempt to describe the moons formation process. Eventually, the scope and structure of the thesis are presented.

1.1. The Jovian system

Jupiter is located 5.2 AU away from the Sun. It is the first planet after the asteroid belt and it is by far the largest in the solar system. It is so big that the centre of the mass of the orbit Jupiter-Sun lays slightly above the solar surface. A Jovian year lasts for more than 12 years due to its distance from the Sun but the planet spins very fast - a Jovian day is less than 10 hours long (Williams 2017).
Jupiter still presents many mysteries. Among the others, the fact that even today it irradiates away more energy than it receives. This is still the heat which was once trapped when the planet formed, similarly to the Earth, for example, where also this heat is still released nowadays, mainly in faults and volcanoes. This also triggers the *Kevin-Helmoltz mechanism*. This phenomenon manifests when a surface of a body cools down (for example Jupiter, or a white dwarf). Due to the temperature decrease, also the pressure experiences a drop, and the body reacts to it by shrinking. Jupiter reduces its diameter by $2cm/yr$ and, following calculations, it has been estimated that its radius was once almost twice as big as it is today (Bodenheimer 1974).
Jupiter possesses a strong magnetosphere, which may be explained by the presence of a metallic hydrogen layer in its interiors. A rocky nucleus is also proposed, where the temperature can reach up to 36000 K and a pressure of 400 GPa, due to the enormous quantity of matter located above (Elkins-Tanton 2011).
The system of objects orbiting around the biggest planet of the solar system is a very particular environment. It owns not less than 79 moons plus a tiny and thin ring system (Sheppard 2018). The moons themselves are either regular and irregular, based on their orbits. Even if the regular ones are only 8, they are quite puzzling and intriguing. They are utterly split into two groups:

- Amalthea group: being named after the fifth biggest moon of Jupiter, Amalthea, they are the innermost satellites. Metis' orbital period, the shortest, takes around seven hours to be completed. They are also maintaining the Jovian faint ring system.

- Galilean group: they are among the biggest moons in the solar system (Ganymede itself is bigger than planet Mercury!). Three moons almost certainly contain subsurface water oceans. They comprise the 99.997% of the mass orbiting around Jupiter. (Kuskov and Kronrod 2005,Clavin 2014).

The Galilean satellites, named after Galileo Galilei who was the first scientist to report them in a book, are very interesting objects. They are extremely massive, compared to all the other moons, and they have a spherical shape (Sheppard 2018). They merit a more detailed description each, as will be done in the following sections.

1.1.1. Io

Io is the closest moon to Jupiter. It is only 421700 km far away from the planet, on average. As comparison, Jupiter seen from the surface of Io would appear to be 39 times larger than the Moon appears from Earth. It takes slightly less than two days to rotate around Jupiter.
It is in resonance with both Europa and Ganymede, respectively in a 2:1 and 4:1 mean-motion. That means that while Ganymede completes one orbit, Europa runs twice around Jupiter and Io four times. This mechanism is called *Laplace Resonance* and it helps Io to maintain its orbital eccentricity of 0.0041. Without the resonance, the orbit would soon circularize due to tidal dissipation, leading to a geologically dead moon (Williams 2017).
The orbit is indeed slightly eccentric. This leads to very huge tidal forces, due to its proximity to the planet, which generate great quantities of heat. Consequently, Io is the most geologically active body in the solar system. It has more than 400 registered volcanoes and its surface is constantly modelled by their action. It is thought to have lava lakes. It is the densest moon in the solar system, reaching 3.53 g/cm^{-3}, almost twice Callisto and Ganymede's density. Its interior are mainly composed of silicates and iron, pretty much similar to a rocky planet than the other moons. Other satellites contain indeed high percentages of a water and ice-silicates mixture (Anderson, Sjogren, and Schubert 1996).
It is probably a differentiated body, with a solid metallic iron-silicate core consisting of 20% of the total moon's mass. Depending on the iron/mass ratio, its radius may extend from 350 to 900 km. Above the core a mafic mantle is found, composed mainly of forsterite, a rock rich of magnesium (Anderson, Sjogren, and Schubert 1996).
Galileo's data indicates the presence of an induced magnetic field on Io. This suggests a subsurface liquid magma ocean which could be as thick as 50 km (California 2011). It is indicated in the figure below as *astenosphere* (fig. 1.1).
The crust of the planet is mainly composed of the Sulfur deposited by the numerous volcanoes. Its thickness ranges from 12 to 40 km (Anderson, Sjogren, and Schubert 1996).
It also own a very thin atmosphere, mainly replenished by the volcanic activity. SO_2 and SO are the most important components (JWSTproposal 2018).

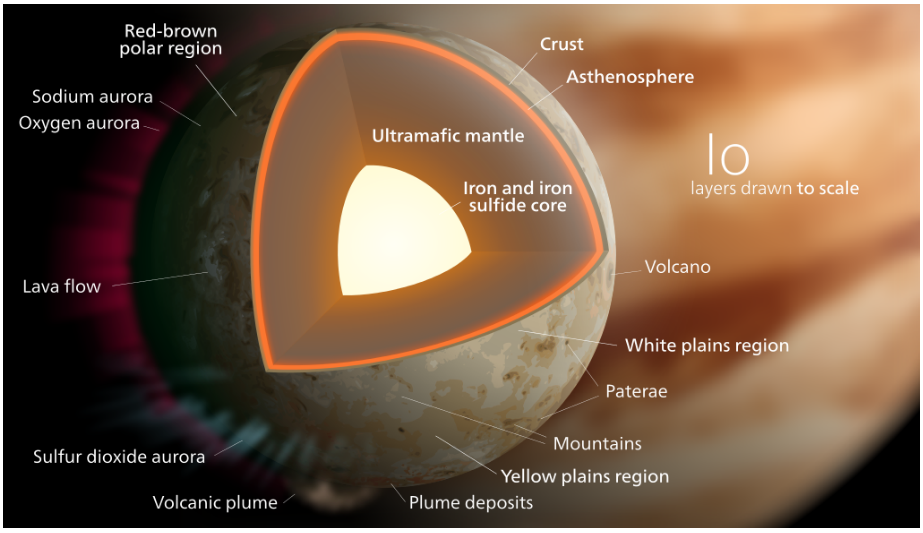

Figure 1.1: Model of the possible interior composition of Io with various features labelled. Courtesy of Kelvin13, Wikipedia user.

1.1.2. Europa

It is the smallest among the Galilean moons. It is in the middle of the well known resonance 1:2:4, between Io and Ganymede. It takes 3 and a half day for Europa to make a revolution around Jupiter being it in a quasi-circular orbit of 670900 km average radius (Kuskov and Kronrod 2005).
Europa probably contains an iron core, though its exact composition and size are still unknown (Kuskov and Kronrod 2005). Above it, a rocky mantle finds place and it extends probably for many kilometres until $\sim$ 100 km from the surface (fig. 1.2).
Its surface is extremely smooth, compared to the other satellites but also considering the other solar system bodies. It is maybe the smoothest. This indicates that the surface must also be very young and malleable. The scientists came up with the following explanation: a subsurface ocean capable of modelling the crust. Probably, its surface has a border layer of ice (30 Km) which very highly covers a thick liquid water ocean (100 km or less). Considering that the average temperature at Europa's equator is 110 K and that at the poles it can reach even 50 K one can wonder how the liquid can exist in such an environment. The extreme cold keeps the ice extremely hard. The water is kept liquid by heating coming from the tidal flexing, a consequence of both the (small) eccentricity and the orbital resonance. It is the same mechanism acting on Io, just in a smaller scale (Kuskov and Kronrod 2005).
It has been hypothesized that some form of microbial life may live in that ocean. In fact, it is an environment with liquid water and a decent temperature (-4°C to 0°C), which could much resemble Lake Vostok, in Antarctica, where small bacteria have been spotted (Chela-Flores 2010).
Europa presents an induced magnetic field due to the interaction with Jupiter's magnetosphere. This can be explained by a subsurface conductive layer, which can be identified with the salty liquid water ocean. Europa owns a thin atmosphere, mainly composed of oxygen (Kuskov and Kronrod 2005).

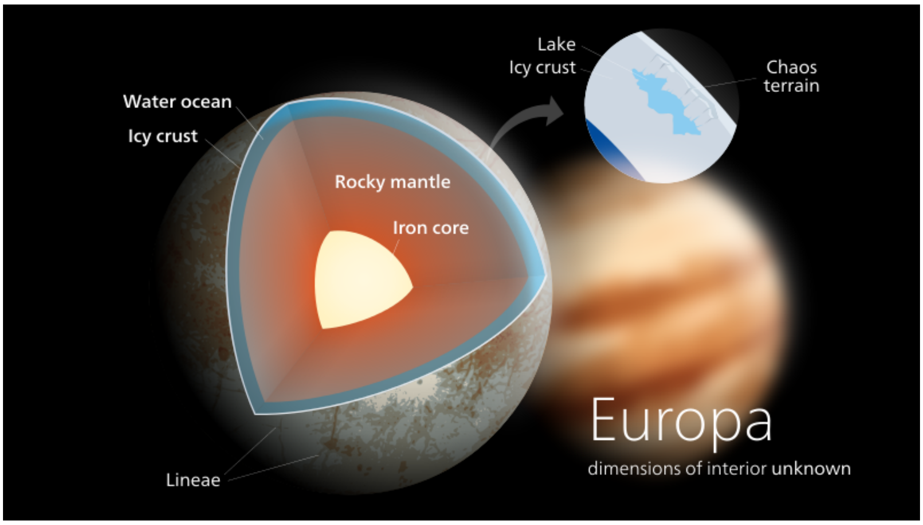

Figure 1.2: Drawing showing the interior of Europa. Courtesy of Kelvin13, Wikipedia user.

1.1.3. Ganymede

Ganymede is the biggest moon in the solar system, with a radius of 5268 km. It is even bigger than one planet, Mercury. But it is less dense, as Mercury is a rocky planet mainly composed of iron and silicates while Ganymede is rich in water, both in icy and liquid forms. Its density equals to 1.936 g/cm^{-3} suggesting, similarly to Callisto, an equal presence of rocks and ices, with an ice/rock ratio of 46-50% (Kuskov and Kronrod 2005).
Also, the exact rocky components are not known but they may look similar to a L/LL chondrite asteroid, where less iron and more iron oxide are present (Kuskov and Kronrod 2005).
This moon is probably fully differentiated (Showman and Malhotra 1999), as shown in figure 1.3. It presents the classical rocky planet structure, with a liquid iron core and a silicate mantle. But, on the contrary of the inner planets, the mantle is very likely covered by a huge ocean (it could be 800 km deep!) and a surface layer mainly composed of ices. It has also been advocated that actually Ganymede may have many oceans at different distances from the nucleus, each one separated by an ice layer (Clavin 2014). It is thought that Ganymede's ocean could be the biggest of the solar system (Kuskov and Kronrod 2005).
Its surface is definitely dominated by water ice, with an ice/rock mass fraction located between 50 and 90% (Showman and Malhotra 1999).
It owns a very thin atmosphere, mostly composed by O_2 and H_2O. This is a direct consequence of the surface dominated by water ice (JWSTproposal 2018).
It possesses a magnetic field, which is thought to be generated by a liquid iron-nickel core. It is however completely buried within the much stronger Jupiter's magnetic field and only produces some local variation (Showman and Malhotra 1999).
Its orbit is particularly interesting as it is in the resonance 1:2:4, corresponding to: Ganymede itself, Europa and Io. This phenomenon is called *Laplace Resonance*. It is possible that in the past the eccentricity of the orbit was bigger than the actual 0.0013, maybe up to 0.02. This could cause a significant tidal heating which the moon cannot experience right now, which could have altered its structure (Showman and Malhotra 1999).

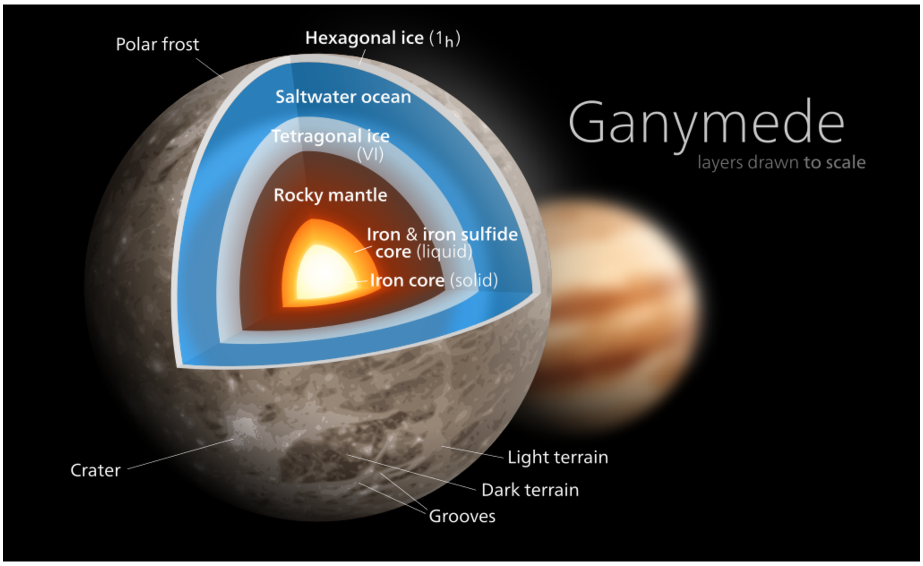

Figure 1.3: Artist's cut-away representation of the internal structure of Ganymede. Layers drawn to scale. Courtesy of Kelvin13, Wikipedia user.

1.1.4. Callisto

The furthest of the Galilean moons is tidally locked to the planet, which means that the same face is always turned towards Jupiter. It is not in resonance. Its orbital period is roughly 16.5 days. Thanks to its distance, it is much less affected by the Jovian magnetosphere than the other moons. In fact, Jupiter magnetic field cannot pass through the planet. This is very likely explained by a layer of conductive fluid (maybe liquid water?) (Kuskov and Kronrod 2005).
Its interior regions are probably only partially differentiated (Canup and Ward 2009). However, Galileo data (the moment of inertia in particular) triggered the idea of a very small silicate core (Kuskov and Kronrod 2005). Plus, it also suggests the presence of subsurface ocean 100-150km, covered by a layer of ice mixed with rocks $\sim$ 100 km thick. In figure 1.4 the core is not portrayed, just a huge undifferentiated centre with the small ocean and the crust above it (Dodd 2010). The fact that it is not differentiated may have very interesting implications into the model of the young Jovian system - it means that its formation process was probably very slow. The lack of tidal heating probably made its differentiation impossible.
It is the least dense of the Galilean satellites, having a density of 1.83 g/cm^{-3} (Kuskov and Kronrod 2005). Similarly to Ganymede, it is thought to have a composition almost equally split by rocks and ice, the mass fractions being respectively 45% and 55%. Also in this case the rock composition may resemble the chondrites (Kuskov and Kronrod 2005).
Its surface is among the oldest and most heavily cratered in the entire solar system. It is possible that the surface has never experienced any geological activity. Spectroscopic observations of the surface have revealed the presence of water ice, silicates and carbon dioxide (Prentice 1999). It possesses a very thin atmosphere composed of CO_2 and O_2 (Dodd 2010).

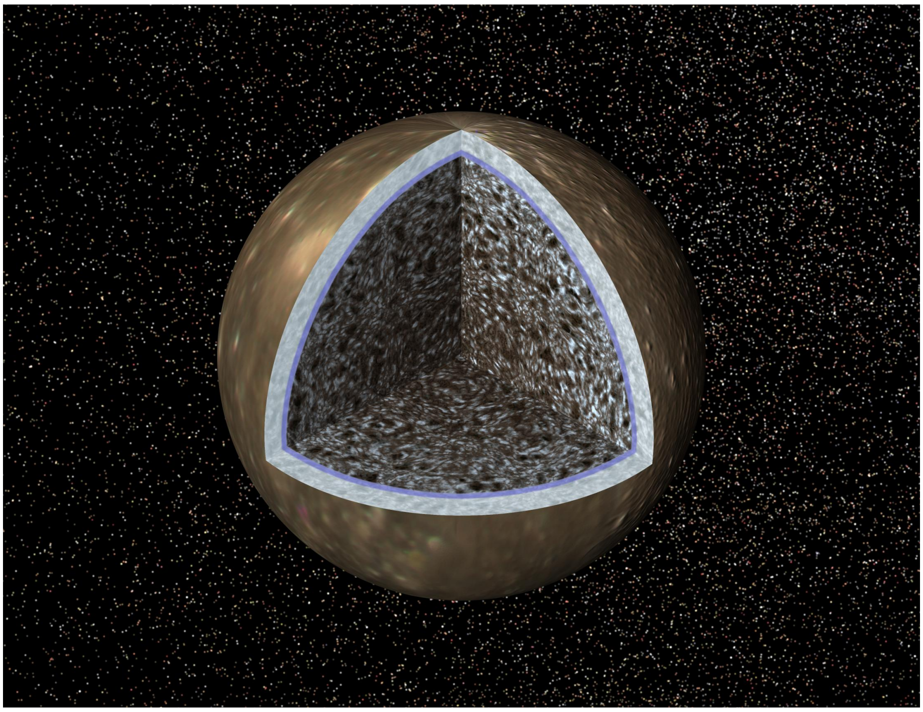

Figure 1.4: Suspected interior of Callisto. The undifferentiated part probably accounts for the major part of the satellite. The outer icy-rich layer is definitely smaller. The proposed thin subsurface ocean is also there. Courtesy of Arizona University.

1.2. Formation theories

During the last century, scientists started asking themselves how these moons could have formed. "hile it is easy to affirm that the smallest and irregular moons have almost certainly been captured, the four Galilean moons pose a great challenge.
Similarly to Triton, the easiest option suggests that these four massive objects were once wandering bodies (for example KBO objects, like the aforementioned Neptune's satellite) which had been captured, at a certain point, by Jupiter. However, some key properties of the satellites rule out this hypothesis:

- The orbits of the moons: they are quasi circular prograde orbit, with very low inclination degrees, in contrast with most of the captured objects in the solar system, for example Triton, which are retrograde.
- They have similar masses.

Therefore, how did they actually form? The main theory currently accepted is that they accreted in a circumplanetary disk around Jupiter, in a way which very much resembles planets' formation (Canup and Ward 2002). But, many questions are still unanswered. A good example is the so-called *Grand Track*. This theory suggests that Jupiter and Saturn both experienced an early migration towards the inner solar system, then they got into a resonance and later moved again into their final actual orbits (Heller, Marleau, and Pudritz 2015). How did this process, if really happened, cope with the formation of the moons? How does the actual composition of the moons help to understand how they exactly formed?

1.2.1. The classical model: the circumplanetary disk

The moons very likely formed in a disk around the planet, in a similar way to which the planets formed in the circumsolar disk. A very nice artistic picture shows this concept in figure 1.5.

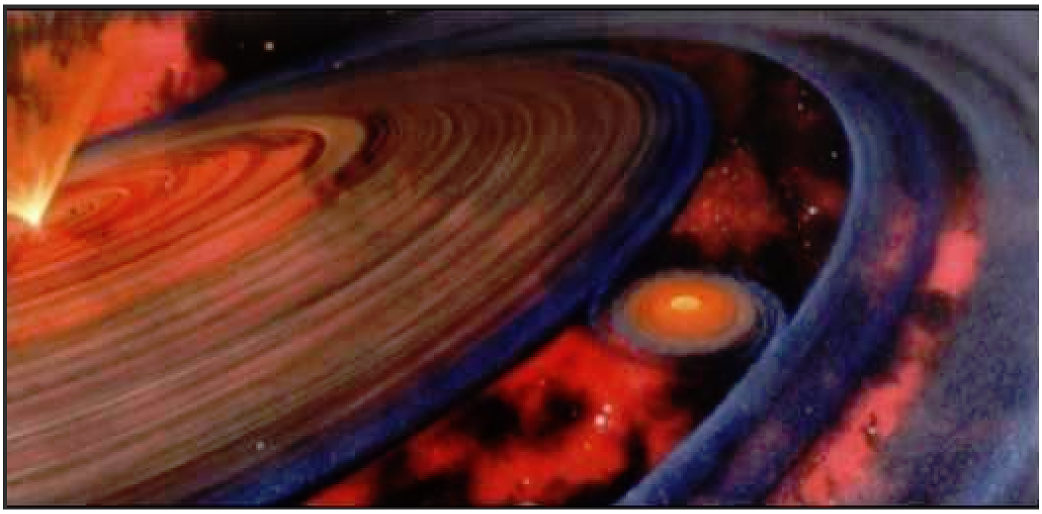

Figure 1.5: Artistic impression of the circumplanetary disk around Jupiter. The opened gap by the accreting planet is clearly visible, alongside with its tiny CPD. Courtesy of NASA.

From simulated contraction timescales, it appears than Jupiter had already contracted within the satellites' region in a shorter time than the expected nebular lifetime. Hence, it is reasonable to think that the contraction and accretion happened simultaneously (Canup and Ward 2002).
The disk formed sometime during those processes. One of the first question which arise is how this disk formed. Around the still growing Sun the residuals of the nebula become the accretion disk from which the protoplanets are fed. But around a protoplanet itself, the things are not so straightforward. From (Canup and Ward 2009), two processes are listed:

- While the planet has started contracting, its surrounding contains the residuals from the solar nebula. In this case, the planet keeps getting smaller and attracts the gas which, at a certain point, has too much angular momentum to utterly fall onto the planet. Therefore, it keeps rotating around the planet forming the so called *circumplanetary disk*.

- A giant gas planet starts to contract when the rate of its gas replenishment via accretion can no more compensate for its increasing gravity due to its growing mass. This happens within its Hill sphere [1] which is, considering the currently density of Jupiter, more than 700 R_J. The accretion gas gives angular momentum to the contracting planet which is also shrinking. Due to conservation of angular momentum, its spin speed also increases. At a certain critical value, Jupiter's equatorial layers started to shed, releasing materials which will form the so called *spin-out disk*.

These models define two different timescales, which must be taken into account while developing this theory. The more realistic hypothesis considers Jupiter that contracts while it is still accreting. It is then surrounded by a CPD. A spin-out disk also emerged during the earliest phases of the contraction, but later the growing accretion disk is dominating the environment and governing the formation of the satellites, once the planet has contracted enough to be smaller than the region occupied nowadays by the Galilean satellites, approximately after 1 Myr (Canup and Ward 2002).
It must be kept in mind that the CPD, even if it may be described as a *mini-solar* system, is a system coupled and dependent on the evolution of the protoplanetary disk. In the model described, the disk evolves in a quasi-steady state and is supplied by a continuous flow of particles while the satellites are forming. Therefore, their growth is dependent on the rate of the supplying flow. It is probable that the disk accumulated (much) more mass than the total of the Galilean moons. Therefore, it has been argued that many satellites may have accreted and later destroyed by a particular phenomenon called *Type I Migration*. The moons which we can observe today are therefore the last surviving generation (Canup and Ward 2002).
The Type I migration is opposed to the Type II. The second consists of the moon migrating away from the planet. The Type I, on the contrary, pushes the satellites towards the planet, a process which would have led to the destruction of the first generations of moons.
From Canup and Ward 2002, the timescale τ in which a satellite decay towards the planet is governed by the following equation:

$$\tau \propto \frac{r^{1/2}}{M_S} \tag{1.1}$$

where r indicates the orbital radius and M_S the mass of the satellite. Hence, it turns out that as a satellite becomes more massive, it also spins faster towards the planet. By reducing its distance, it utterly accelerates the decaying process resulting in a catastrophic collision (Canup and Ward 2002).
Canup and Ward 2002 cited more constraints on the moons formation environment, such as:

- They have considered the so called *gas starved* disk, which means that the mass of the solids in the CPD was about $\sim 10^{-2}/10^{-3}$ the sum of the satellites' mass, or $\sim 10^{-6}/10^{-7}\ M_J$ (Konrod and Makalkin 2017).
- A low enough temperature allowing Ganymede and Callisto to accumulate water ice in great quantities.
- Slow accretion process (more than 10^5 years), given the incomplete differentiation of Callisto.
- An inflow rate of mass from the PPD of $10^{-7}\ M_J$/yr.

Eventually, considering all factors, it is thought that the moons formed within a temporal time of 1-10 Myr from the beginning of Jupiter's formation process (Canup and Ward 2002).
The accretion disk model described the Galilean moons formation as a consequence of the formation of Jupiter. Considering the estimated timescales, the planet contracted well before the solar nebula was completely dissipated and hence it enabled the formation of an actively supplied circumplanetary disk. It is also generally accepted that many more satellites were formed and, once reached a certain threshold value, they migrated too fast towards the planet and consequently have been destroyed, until the CPD runs out of material, stopping the accretion of the moons (Canup and Ward 2002).
Within some million years, the dissipation of the nebula occurred, and hence the supply to the disk stopped. This pretty long temporal interval can explain the low temperature needed to enable ices accumulation on Ganymede and Callisto; also consistent with the partial differentiation of Callisto.

[1] The Hill sphere is the region where a smaller body's gravity starts to dominate the environment opposed to the main one. In this case, Jupiter's attractive force is stronger than the solar one.

Last but not least, it is also thought that the disk temperature at the location of Europa was too warm to form ices, at least in the earliest stages of the formation. As the formation was coming towards the end, the young Jupiter was also cooling down - this lead to a shift of the ice line within Europa's orbit. This could explain how this satellite mostly accreted as a rocky object (similarly to Io) with a final layer of mixed rock and ice. This is in line with the higher density of Europa, smaller than Io's and greater than the other two moons' density (Canup and Ward 2009).

1.2.2. The ablation, as a key component in the formation process?

Orbiting around Saturn a particular moon, Iapetus, has been discovered. It has an unusual low density and it is very rich in ice. This inspired the development of the following model, described in (Mosqueira and Estrada 2003).

Due to the formation of the gas giants, the planetesimals in their regions got dynamically excited. A lot of collisions happened releasing huge amount of debris, probably enough to comply with the mass budget of the moon systems. Icy objects are, in general, easier to be captured and ablated[2] than rocky bodies. In fact, icy objects need a lower temperature to ablate, either due to vaporization or melting. Especially at large distances from the planet, this difference increases also due to the lower orbital velocities, which reduce the number of impacts and the chances of high temperatures. This gives a good explanation for the large quantities of ice in the outer moons of Jupiter (Callisto, Ganymede) but also considering Iapetus, whose density of $1.081\ g/cm^3$ is just above the one of water (Mosqueira and Estrada 2003).

The model also starts considering the regions surrounding the forming gas giants. A lot of collisions happened among the planetesimals, resulting in ~ 10 km sized bodies. The model assumes them to be at least partially differentiated, so that a non homogeneous population of fragments can form. Later on, they will ablate through the circumplanetary disk. Given the same size, at great distances from the centre, the disk is less dense and the rotating bodies are slower. Hence, icy fragments are able to ablate while rocky objects are not. The temperature of the rocky bodies will therefore not be high enough to melt them. This will ultimately result in a icy-water enrichment of the outer disk. This explains the scaled compositions of the Galilean satellites, as well as the difference between Titan and Iapetus (Mosqueira and Estrada 2003).

Considering the small radial mixing expected in the disk, the radial composition is reasonably thought to have preserved throughout the years as can still be observed right now (Mosqueira and Estrada 2003). This paper was also the first to introduce the so called *minimum mass* disk. This is the simple algebraic sum of the solid masses of the Galilean satellites. This is a very dense model, and its solid mass is equal to $2 \cdot 10^{-4}\ M_J$corresponding to a total disk mass of $2 \cdot 10^{-2}\ M_J$, assuming the classical interstellar dust to gas ratio of 0.01.

1.2.3. The pebbles accretion model

The work by Ronnet, Mousis, and Vernazza 2017 presents both similarities and differences with the previous ones.

It suggests that one of the most important constraint concerning the moons' formation environment, and the following evolution, is the gradient in water mass. Io has in fact no water at all, while Europa has an 8% in water mass and the other two outer moons have a percentage of water larger than 50%. According to Mosqueira and Estrada 2003, the increasing radial velocity of the bodies closer to the planet, is responsible of highly energetic impacts leading to substantial water losses.

A possible explanation for this difference in water gradient is related to the snowline, as suggested by Lunine and Stevenson 1982. This is related to the decreasing temperature with increasing distance from Jupiter. In this scenario, the inner moons accreted in a water-poor environment while Callisto and Ganymede had plenty of water in their accretion regions. However, Europa's origin is still quite uncertain. It may be depending on the moon migration during its formation and/or a shift of the snowline due to the cooling down of the disk.

In any case, it seems that Europa's shape and interiors depend on its formation within the CPD rather than post-formation phenomena. In this research, the formation conditions of the Galilean moons were analyzed modelling the transport of solids within the CPD, focusing on the evolution of the so-called

[2]Ablation: it consists of the removal of particles from the surface of a body, in this case small rocky/icy bodies orbiting around planets. It is the result of the vaporization of the upper layers due to high temperatures which follow an impact.

pebbles, during the late stages of the formation of Jupiter. The pebbles are by definition bodies having a diameter $\sim 1 - 10cm$. The model is quasi-stationary, and its scopes are to calculate firstly density and temperature distributions, followed by radial and azimuthal velocities of the gas. The equations of motion of the solid particles have been numerically solved (Ronnet, Mousis, and Vernazza 2017). The temperature profile of the simulated CPD is illustrated below in figure 1.6.

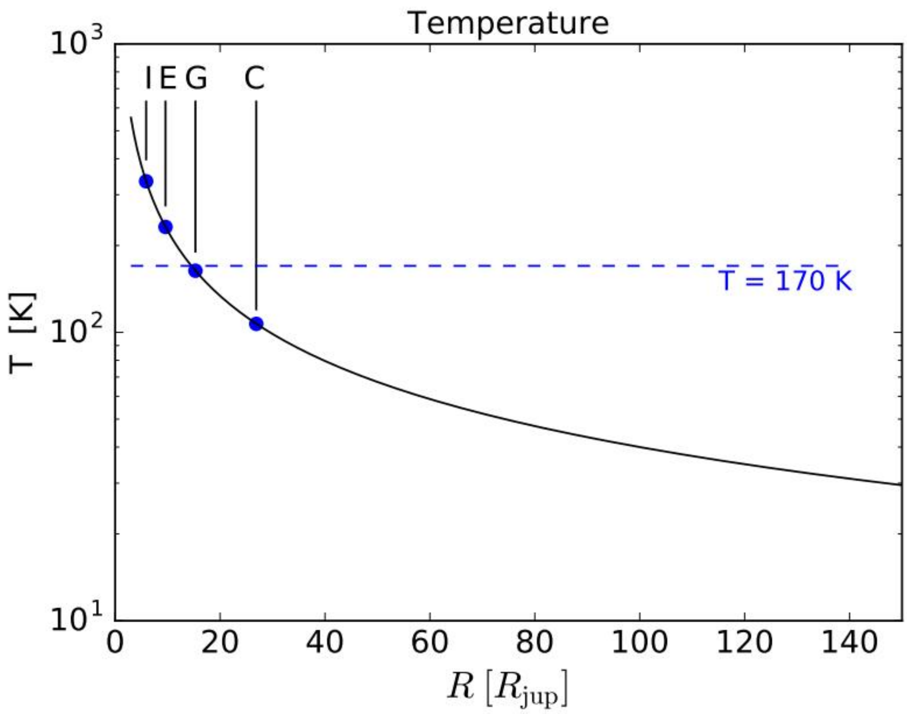

Figure 1.6: The temperature profile of the CPD, as computed in the model, having a coefficient of turbulent viscosity $\alpha = 10^{-3}$ and a mass accretion rate of $\dot{M} = 10^{-7}\ M_J$/yr. The letters indicate the position occupied by the moons nowadays. The dashed line indicates the postulated water ice snowline at T = 170 K. Courtesy of Ronnet, Mousis, and Vernazza 2017

From the results (see figure 1.7, it appears that the size does play a very important role in the ability of a particle to keep water while drifting inwards. Smaller particles (10^{-1}m) are less capable of retaining water compared to kilometre-sized objects. If these smallest particles were the ones mostly involved in the accretion of the moons, then Io and Europa should probably have much more water than they have today. Therefore, the smaller candidates (the pebbles), coupled with quick formation times, seem to be a realistic scenario (Ronnet, Mousis, and Vernazza 2017).

In figure 1.7 the results of three different simulations are shown. 10^4 particles have been randomly released in the region comprised between 25 and 35 R_J. Afterwards, the simulation was started scattering the particles around the CPD. The changing parameter was the size of these particles, as indicated in the legend.

This paper showed that a pebble accretion process is an interesting candidate for the formation of the Galilean satellites. The fast inward drift of the pebbles possibly led to a quick definition of the three different regions in which the moons accretion took place. This however implies that the pebbles do not completely burst when crossing the snowline. Also, each moon must have been fully formed in its own specific region. This means either that the snowline did not move or that the forming satellites moved with the snowline, which has been recently investigated (Ronnet, Mousis, and Vernazza 2017).

1.2.4. The formation of the Galilean moons in the Grand-Track scenario

Heller, Marleau, and Pudritz 2015 have studied the formation of Galilean moons in an approach similar to the one proposed in this thesis.. They consider the proposed Grand Track scenario in which Jupiter formed beyond 3.5 AU and therefore experienced an inward migration until 1-1.5 AU, when it entered a resonance with Saturn. Thereafter, both the gas giants migrated backwards until their present location

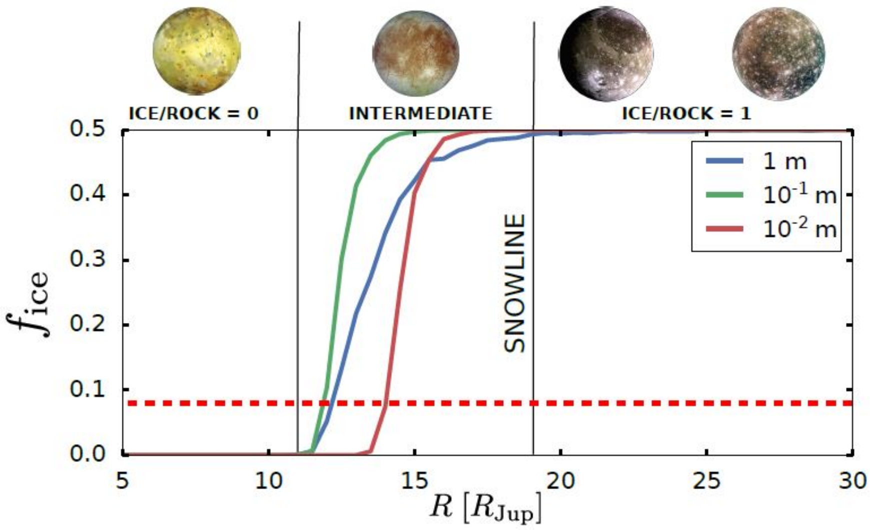

Figure 1.7: Average water ice mass fraction as a function of the radial distance from Jupiter. The dashed line indicates the current water mass fraction estimated for the moon Europa. The three colours indicate different initial sizes for the aggregating bodies. Courtesy of Ronnet, Mousis, and Vernazza 2017

- with Jupiter ending up at $\sim$ 5.2 AU. This mechanism explains the presence of many hot Jupiters in other stellar systems which cannot form so close to a star and must have originated further, similarly to Jupiter.

They argue that the moons necessarily formed either before or after the migration since the Sun would have been too strong to allow the formation of icy moons when Jupiter was too close. In particular, they postulate that the satellites could have also atmospheres, similarly to Titan. These primordial atmospheres would have been later swept away by the young Sun during the migration. They also argue that the Saturnian system had never reached such a critical distance where the Titan's atmosphere would have been wiped out.

1.3. This thesis

The idea is to make different scenarios considering some of the several input parameters which can be given to ProDiMo. The final equilibrium shall therefore be analyzed to understand, for example, if the chemical distribution of the CPD corresponds to what the moons are composed of today. Or, at least, scaled to a certain degree. In that case, the migration of the moons and/or the shift in the snowline could still explain the differences, if other regions of the CPD would be more in line with the moons' compositions (Ronnet, Mousis, and Vernazza 2017).
Ideally, the mass of the CPD should be identified. Was it constant or was it changing, maybe because of a link with the PPD?
Other unknowns are, for example, the contribution of the young Jupiter and Sun to the power budget of the CPD. So far, the previous authors have always defined themselves a temperature profile for their simulations. With ProDiMo, the temperature profile is not an input but rather an output, which makes it very interesting for comparisons with the other simulations where the profile is simply given.
The migration of the planet is something which has been considered only once in the previous models. This is because it is thought to happened many hundreds of millions years after their formation, when the Galilean moons would have been already formed. However, it is important to verify if and how much the closer young Sun could have affected the CPD. Other simulations, taking that into account, should also be carried out. Heller, Marleau, and Pudritz 2015 tried to assess this aspect, and the results will be compared.
Last but not least, did the PPD influence the moons' formation? If so, what was its role and how much did it influence? Was there a constant inflow of mass from the PPD into the CPD, as expected in Canup and Ward 2002? If this happened, it very likely had a strong impact on the history of the CPD.
There is a long list of parameters which must be considered. Many different scenarios will be simulated, where the different effects will be treated individually. Some fiducial models will be defined, as bases for the next iterations of simulations. The results will then be analyzed with a Python tool, called prodimopy.
An interesting thing to observe is the position of the different snowlines, deduced by the ice abundance plot of each species within the disk. As reference, figure 1.6 gives an idea of what the temperature profile could have been. Here, the snowline of H_2O is also indicated as T = 170 K. However, it must be recalled that this value is not unique as the freezing temperature depends on many parameters. Miguel and Ida 2016 use 180 K while Mosqueira and Estrada 2003 use 220 K. Obviously other snowlines exist, such as NH_3, CO_2 and CO. The temperature which is reached in the CPD sets the type of ice that we would get. Therefore, the composition of the moons could help us understand their formation mechanism.
As mentioned, one of the major final goal is to deliver the expected compositions of the disk where the moons formed based on the simulations. These data will ideally be compared with the findings of the European probe JUICE, to be launched in June 2022, or the American Europa Clipper. Possibilities of comparison are also open with the observations which will be carried out by JWST. These comparisons would either confirm the scenariow proposed in this project, or provide hints for future simulations. Ronnet, Mousis, and Vernazza 2017 argues that the composition of the moons which can be observed today is a direct consequence of the way in which the satellites formed in the CPD, since they have not undergone any significant post formation process. Due to this reason, this proposed thesis which promises to deliver detailed information on the expected composition of the CPD disk, could greatly help in determining the exact process and initial conditions.

1.3.1. The aims

The previous section tried to present the problems which we intend to tackle in this project. In order to focus the effort and having already clear in mind what the goals are, the text is summarized into a list of to-be-answered questions, which is hereby presented. The main research question, the one leading the whole project, follows:

In what conditions did the Galilean moons form?

Other research questions, related or deriving from the main one, are listed below:

- What where the initial conditions of the CPD? Its sizes, mass, composition, are not known yet. Only rough guesses have been theorized.

- Did the planetary migration play a role in the process?
- What was the SED of the young Jupiter, and how much did it influence the moons' formation?
- How much time did the process require?
- Was the CPD disk coupled with the PPD? If so, how much matter were they exchanging?
- What is the expected compositon of the CPD in the different scenarios?

All these questions will be addressed through computer simulations, carried out with the ProDiMo software. It will be briefly introduced in chapter 2.

1.3.2. The structure of the report

The thesis will be structured as follows. In chapter 1, the introduction on the Jovian environment and a general overview of the theories concerning the formation of the moons constitute a strong theoretical basis useful for a better comprehension of the following chapters. The next chapter 2 presents a short description of the software, ProDiMo.
In chapter 3, the main parameters determining the CPD characteristics are investigated. These cover the work done behind the determination of the young Jupiter and the circumjovian disk properties. This will lead to the definition of the first fiducial model.
Chapter 4 will try to provide different scenarios, considering the many effects which have not been investigated yet. From chapter 3 the so far produced CPD is completely frozen, while the leading hypotheses states a water ice snowline present at Europa's current orbit. The new iteration of simulations in chapter 4 will lead to the definition of a second fiducial model.
In chapter 5, starting from the results of the previous chapter, the new fiducial model is better characterized. Alternative models are investigated, including for example CPDs with different masses.
Chapter 6 shows the expected chemical abundances of the ice in the regions today populated by the Galilean moons. This is done for certain selected models which we consider, based both on the results and the current theories, the most probable scenarios for the Jovian CPD.
The report will end with the conclusions presented in chapter 7. Some recommendations for future work with ProDiMo and research in the challenging but fascinating topic of the moons' formation process are given.

2

The software: ProDiMo

The software used during the thesis, ProDiMo, will be briefly introduced in the following pages. The chapter will start with an introduction on the general phylosophy of the software, later on moving onto a more detailed descriptions of its modules and key parameters. Other minor things will also be described, such as the ProDiMo day and prodimopy.

2.1. A general presentation

The acronym of the software, ProDiMo, stands for PROtoplanetary DIsk MOdel. It was first conceived almost ten years ago and presented in the first paper where it was used to study the hydrostatic structure and inner region of a protoplanetary disk (Woitke, Kamp, and Thi 2009).
As described by one of its author, Peter Woitke, "ProDiMo is a F90 software package to simulate protoplanetary disks including astro-chemistry, detailed gas heating and cooling balance, and continuum and line radiative transfer in 2D symmetry" (Woitke 2013).
ProDiMo has a series of important assumptions:

- The main one is that the considered disk is in a steady state - any dynamical evolution of the structure is neglected.
- The disk is azimuthally symmetric and the physical quantities considered only vary depending on the radius r (the distance from the center) and the height z (the disk midplane is located at $z = 0$).
- The disk is exposed to stellar and interstellar radiation, which are the main sources for the heating of the gas and the dust and determines their temperatures, which are decoupled.

The idea is to play with different species and their correlated chemical reactions, until an equilibrium is reached. The program gives an enormous amount of text files as output. Those need to be processed and plotted in order to be able to understand what is going on. The easiest way to do so is to make use of an already existent routine written in IDL (Interactive Data Language), by the same creators of ProDiMo. IDL is massively used by the astronomic community of both scientists and engineers and the development company claim it has more than 150,000 users. But, its licence is really expensive. An alternative Python based solution, called prodimopy, has been designed. It will be presented later in section 2.3.

2.2. The structure of ProDiMo

The diagram in figure 2.1, drawn by Christian Rab, shows the cycle followed by ProDiMo when it is run. The code starts from the definition of a fully parameterized fixed disk structure structure of the disk, based on the related inputs, like its mass and dimensions. It is possible to let ProDiMo solve the vertical hydrostatic disk structure, but this will not be applied in this project. The density structure is calculated according to equation 2.3, which will be extensively discussed later.

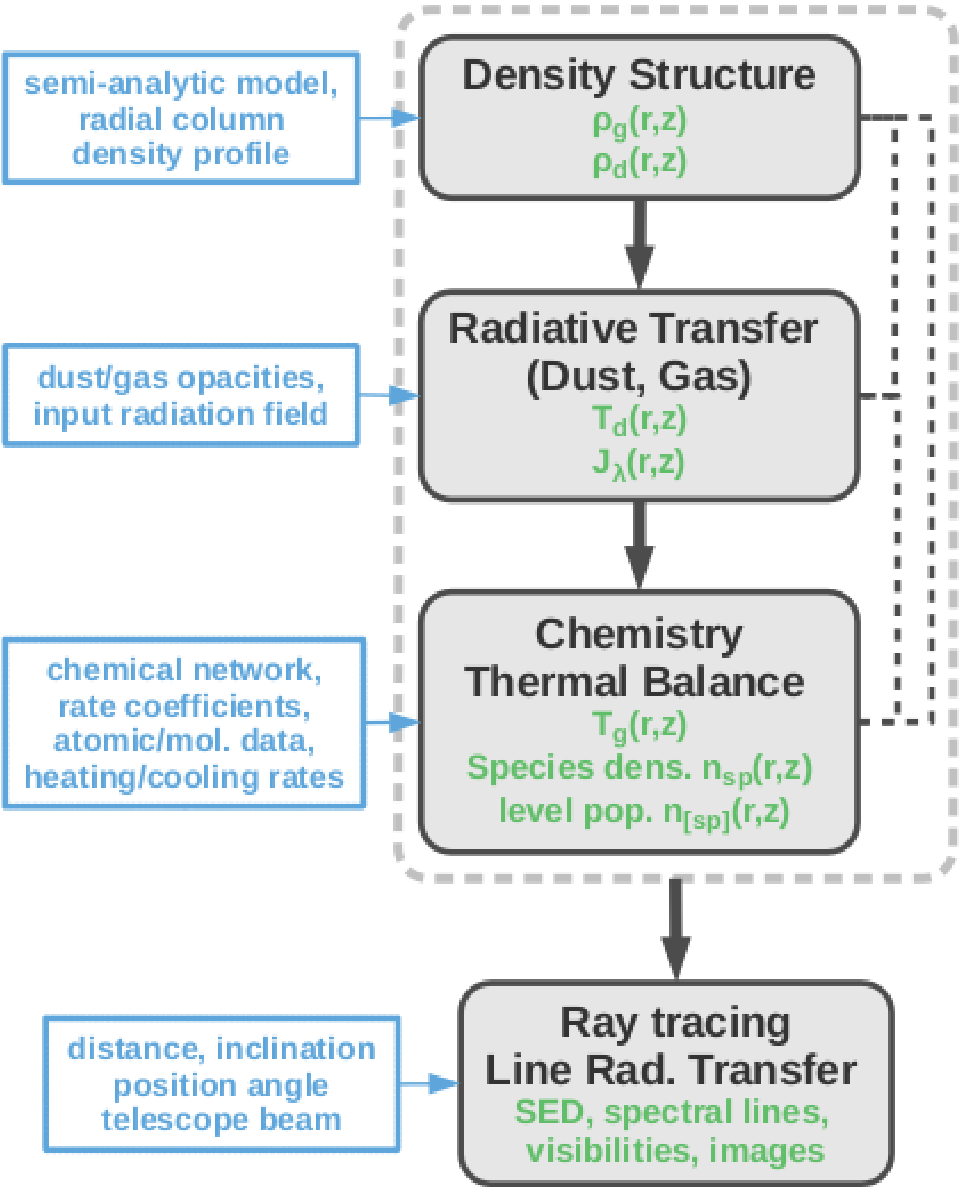

Figure 2.1: The structure of ProDiMo. Courtesy of Woitke 2013

In the second module of ProDiMo shown as the grey box ”Radiative transfer”, the radiation sources are considered and their effects are analyzed throughout the disk. The stellar and interstellar radiation fields heats up the dust and the gas. These are usually the leading parameters for the disk temperature. The radiation field needs to be known in every sector of the disk as it plays a crucial effect for the chemistry. This module of ProDiMo can also model other things, such as the X-ray radiative transfer and PAHs emission.
The third module is the core of the software, as it handles all the chemistry going on inside the disk. For every species the following rate equation applies:

$$\begin{aligned}\frac{dn_i}{dt} = &\sum_{j\in F_j} k_j(T_g) n_l n_m + \sum_{j\in F_j^{phot}} k_j^{phot} n_l + \ldots \\ &- \sum_{j\in D_j} k_j(T_g) n_l n_m - \sum_{j\in D_j^{phot}} k_j^{phot} n_l - \ldots\end{aligned} \tag{2.1}$$

The derivative of the number density n_i is given by the sum of all the reactions which forms (first row) and destroys (second row) the analyzed species. In equation 2.1 only two processes are shown, the gas phase and photo reactions. ProDiMoactually contains thousands of different processes which form or destroy the species. The rate coefficients k depends on the gas temperature T_g, which is computed by the thermal balance 2.2 considering every heating and cooling process.

$$0 = \sum_k \Gamma_k(T_g, n_{sp}) - \sum_k \Lambda_k(T_g, n_{sp}), \tag{2.2}$$

where Γ_k and Λ_k indicate respectively the sum of the various heating and cooling rates, T_g is the aforementioned gas temperature and n_{sp} the species number density.
Through the equations 2.1 and 2.2 ProDiMo can compute the gas temperature and species abundances in every point of the disk.
The last module is used to generate synthetic observables, such as the SED of the star and spectral emission lines from the gas. This is useful to compare the outputs with real observations. The software gives the options to select the wavelength, or the distance and inclination of the hypothetical observer.

2.2.1. The stellar model

The scope of ProDiMo is beyond the determination of the stellar SED used in the simulations. However, it is a vital parameter for this kind of simulations. To cope with this need the creators decided to make use of already available stellar spectra. The choice fell upon the so called PHOENIX models, created by Baron et al. 2003. They include a set of thousands of different modelled stars, where they consider three varying parameters: metallicity, logarithm of the gravity surface and effective temperature. However, this model has a real big limitation - the effective temperature cannot be pushed lower than 3000 K. This is very inconvenient because a young Jupiter's temperature is probably around 1000 K, but very reasonably even lower. To mitigate this inconvenient, at least for a first approximation, a freshly introduced functionality has been used - the so called DRIFT-PHOENIX model.
Briefly speaking, it is an expansion of PHOENIX - in addition, it is capable of simulating the behaviour of an atmosphere, including the effects of clouds. DRIFT was originally a separate code, with the purpose of analyzing the formation and properties of clouds, such as size and composition, see Woitke and Helling 2003 for more details. It was later on coupled with PHOENIX to obtain a way broader range software, capable of showing "*atmospheres and spectra of stellar object all across HR-diagram ranging from main sequence stars, giants, white dwarfs, stars with winds, TTauri stars, novae and supernovae, to brown dwarfs and extrasolar giant planets*" (Witte, Helling, and Hauschildt 2009).
Each stellar model contained in the PHOENIX library is defined by the following the parameters:

- Metallicity, ranging from -0.6 to 0.3, in steps of 0.3.
- Gravity surface g, expressed in a logarithmic scale, from 3.0 to 5.5 in steps of 0.5.
- Effective temperature[1] T_{eff} expressed in Kelvin, ranging from 1000 to 3000, with a step of 100 K.

ProDiMo however, requires as well three inputs, but they are partially different from the PHOENIX parameters. They are:

- The stellar effective temperature, expressed in Kelvin. This is the common parameter.
- The stellar luminosity ratio, with respect to the solar luminosity.
- The stellar mass ratio, with respect to the solar mass.

The choice for the adoption of these parameters is pretty logical; they are easier and handier to be treated by the user. The stars, in the classical Hertzsprung-Russell diagram, the x and y axes are respectively the temperature and the luminosity, while in the diagram itself the mass of the stars are mentioned. For this reason, these three parameters have been chosen.
Based on the input values, the software itself determines what is the model which best fits. An example

[1]The effective temperature of a star is the temperature of the black body which would emit its same amount of radiation. Often the surface and the effective temperatures are approximated to be the same value.

output of a TTauri star can be seen in picture 2.2.
ProDiMo has an interesting feature when it comes to analyze the SED of both the disk and the star model. Among the others, there is the possibility to select a desired distance (in parsec) and inclination (in degrees) where a hypothetical observer is placed. It is a very useful tool, which can be used for example to compare the results with observational data, or other models, in order to give a first qualitative comparison to the output of ProDiMo.

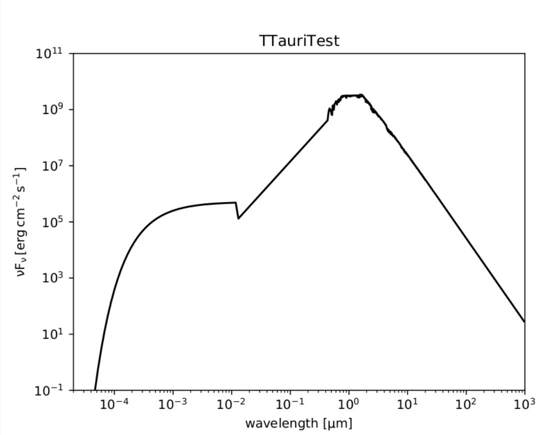

Figure 2.2: Spectrum of a TTauri star having 0.7 $M_{\odot}$, 1 $L_{\odot}$ and 4000 K as effective temperature. This is as it would be seen from a distance of 140 pc.

2.2.2. Other sources of irradiation

Other parameters governing the sources of energy different than the star are shown in picture 2.3.

```
0.01         ! fUV        [-]       : LUV/Lstar
1.3          ! pUV        [-]       : UV powerlaw exponent
.true.       ! Xrays      [-]       : use Xray chemistry and heating?
1.E+30       ! Xray_Lum   [erg/s]   : X-ray luminosity
2.E+7        ! Xray_Temp  [K]       : X-ray emission temperature
1.7E-17      ! CRI        [1/s]     : cosmic ray ionisation of H2
1.0          ! CHI_ISM    [-]       : strength of incident vertical UV
```

Figure 2.3: A screenshot of the Parameter.in file. It shows the inputs for all the irradiation sources excluding the PHOENIX models parameters.

A brief description of them follows:

- CHI_ISM default value is 1, which is the effect of the cosmic background radiation. It can be increased to take into account other effects, for example the Sun, in our particular case.
- CRI stands for Cosmic Ray Ionization of H_2 molecules (Chaparro Molano 2013).
- fUV and pUV describe the ultraviolet contribution of the stellar SED. The straight line of figure 2.2, located in the wavelength region $0.2 - 4\ \mu m$, is determined by those two parameters, being fUV the starting point from DRIFT-PHOENIX and pUV its inclination.
- X-rays parameters form the rest of the left part of the SED, where the wavelength is $< 0.02\ \mu m$.

2.2.3. The disk model

ProDiMo offers a wide range of options for the different properties of the disk. An example of a typical Parameter.in file, with a focus on the disk properties can be seen below:

```
------ dust parameters ------
0.05         ! amin         [mic]   : minimum dust particle size
3000.0       ! amax         [mic]   : maximum dust particle size
3.5          ! apow         [-]     : dust size distr f(a)~a^-apow
***2            ! settle_method        : dust settling (Dubrulle et al. 1995)
***1.E-2        ! a_settle             : turbulence alpha
***0.8          ! hollow_sphere        : max hollow volume ratio
dust_opacity_list2.txt              ! dust_opacity_list_file
3            ! NDUST                : number of selected dust species
  0.60       Mg0.7Fe0.3SiO3[s]
  0.15       amC-Zubko[s]
  0.25       vacuum[s]

------ PAH parameters ------
0.01         ! fPAH         [-]     : PAH abundance with respect to ISM
.false.      ! PAH_in_RT            : are PAH opacities included in rad.trans.?
.false.      ! PAH_from_RT          : PAH heating from cross-sections?

------ gas parameters ------
0.01         ! dust_to_gas [-]      : the dust-to-gas mass ratio
0.2          ! ChemHeatFac [-]      : efficiency of chemical heating
.true.       ! UMIST2012
.true.       ! Eads_from_file       : use UMIST2012 adsorption energies
onlyadd      ! handle_UMIST         : handle UMIST-data (erase/overwrite/onlyadd)
0            ! num_noerase          : exceptions from erasing UMIST data

------ disk mass & shape ------
.false.      ! solve_diskstruc      : solve the vertical hydrostatic eq.?
.true.       ! MCFOST_LIKE          : parametric disk structure like in MCFOST?
0.00000015         ! Mdisk       [Msun]  : disk mass
0.001       ! Rin          [AU]    : inner disk radius
0.007          ! Rtaper       [AU]    : tapering-off radius
0.072        ! Rout         [AU]    : outer disk radius
1.0          ! epsilon      [-]     : column density exponent
10.0         ! MCFOST_H0    [AU]    : scale height ...
100.0        ! MCFOST_RREF [AU]     : ... belonging to reference radius
1.15         ! MCFOST_BETA          : flaring power
```

Figure 2.4: A screenshot of the Parameter.in file. Only parameters and switches are present.

In figure 2.4 a representative of the parameters is shown. Not all of them have been altered in the project, and have been kept to the default values.
The first two parameters are self explanatory, they define the minimum and maximum size of the particles present in the disk. The third defines the power value of the dust distribution law, which works as follows:

$$\rho(r,z) = \frac{\Sigma(r)}{\sqrt{2\pi}\cdot h(r)} exp\left(-\frac{z^2}{2h(r)^2}\right) \qquad [g/cm^3], \tag{2.3}$$

where ρ is the density, depending on height z and radius r, Σ is the radial surface density profile and h represents the vertical scale height, both depending on the radius r (Woitke, Kamp, and Thi 2009). For the fully parameterized disk, the scale height is computed according to equation 2.4.

$$h(r) = H(100au)\left(\frac{r}{100au}\right)^{\beta} \qquad [au], \tag{2.4}$$

where $H(100au)$ is the reference scale height at $r = 100au$.
Other parameters include the dust to gas ratio, some numbers describing PAHs' abundancy and effect, the inner and outer radius.

2.2.4. The viscous heating

ProDiMo allows also to specify the mass accretion rate of the disk. This parameter goes under the name of $Mdot$, which is expressed in solar masses per year. If this parameter is specified, then the software considers the equation 2.5, stating that the half column (i.e. at z = 0) heating rate at a certain radius is (D'Alessio et al. 1998):

$$F_{vis}(r) = \frac{3GM_{star}Mdot}{8\pi r^3} \cdot \left(1 - \sqrt{\frac{R_{star}}{r}}\right) \qquad [erg/cm^2/s], \tag{2.5}$$

in which it is assumed that $Mdot$ is constant throughout the disk, and that a certain part of the gravitational energy released when the disk shrinks is converted into heat. To turn this heating rate per column into a heating rate per volume, an additional assumption on how the total heating rate is distributed within the column as function of height z is needed, expressed in equation 2.6.

$$Gamma_{vis}(r,z) = \frac{F_{vis}(r)\rho^2(r,z)}{\int \rho^2(r,z')dz'} \tag{2.6}$$

Setting the switch $dust\_nonRE$[2] to true guarantees that the viscous heating is applied to both the gas and the dust.

2.2.5. Applying a background temperature

ProDiMo allows the user to specify a background temperature, which goes under the name of $Tback$. The default value is 2.7 K , which corresponds to the cosmic microwave background radiation. However, it can be raised to simulate a warmer environment in which a disk can form. For example, the Jovian CPD was embedded in the Solar PPD, which was much warmer than the default 2.7 K.
$Tback$ also needs to set to true a switch called IR_ISRF, which stands for Infra-Red Inter-Stellar Radiation Field. The philosophy behind $Tback$ thus consists of "diving" the simulated disk into a uniform infrared radiation field, warming it up to the selected value. It must be noted that the strongest effect will be on the external shell of the disk and it will decrease proceding inward.

2.3. Prodimopy

ProDiMo output files have been designed to be easily interpreted by IDL. It is unfortunately a very expensive licensed software which cannot be afforded by a regular student. Hence, it was necessary to develop something new, possibly using an open source free software. The choice fell upon Python, which is a open source high level programming language, which is taking the lead among the engineering community. It can be used for various purposes, ranging from electrical circuits simulations to CFD analysis. It is a very versatile language which can be easily used, even by a non experienced programmer.
Christian Rab, who wrote a PhD thesis using ProDiMo, has already completely developed and implemented a good working version of prodimopy, where most of the interesting routines, such as the SED of the star and the disk, the density gradient of the species, and many more are already present (Rab 2018).
In this project new features will be added, together with a modification of the existent ones. For example, the default output file of ProDiMo plots the distances in AU. Given that a $R_J \sim 0.0005$ AU, it is more convenient to express the distances in R_J. Hence, the plotting routines will be edited to use R_J instead of AU.
Prodimopy is capable of plotting almost all the routines which were once only available via IDL. These range from SED of the disk and the star, temperature profiles and contours, density distribution, heating and cooling processes' rates and various species and elements densities in the disk. Many of these routines will be used and shown later in this report.

[2] $dust\_nonRE$ indeed stands for dust **not** in radiative equilibrium

2.4. ProDiMo day

The 10^{th} of April the TU Delft ProDiMo using community, as well as other people from Amsterdam and Leiden, gathered together at the Kapteyn Astronomical Institute in Groningen. During that day, the software was introduced and some of the most interesting tricks and features were explained by the own creators and the most experienced users, including persons who have produced their PhD dissertations and other great scientific papers using ProDiMo.

The first part of the day was dedicated to a general presentation of the software itself. Christian Rab, Peter Woitke and Inga Kamp explained to the audience the basics of ProDiMo and some among the fastest and most effective ways to analyze the results.

The afternoon was more personal. The aforementioned skilled persons helped the newcomers with the resolution of their first (sometimes) trivial problems in order to get started as soon as possible with their own researches.

With respect to this thesis, the first attempt was carried out. The results were as expected quite weird and show an enormously warm Jupiter, with a snowline located as far as 100 R_J and will therefore not discussed any further. It was mostly an attempt to assess the functionality of the program with the very particular conditions needed in this project.

3

Describing the early Jovian system

The scope of this chapter is to present the path followed to establish the characteristics of the young Jovian system, the environment in which the satellites of Jupiter formed. All these information are crucial for ProDiMo as they define the boundary conditions for the thermo-chemical simulations. Then, the first simulations' results are showed and discussed, as well as with the plans for the next steps.

3.1. Circumplanetary vs protoplanetary disks

ProDiMo has been thought and designed to cope with protoplanetary disks which are, as one may guess from the name, those disks of gas and dust orbiting around young stars from which the protoplanets form and consequently accrete until they reach the final stage of planet. For terrestrial planets, the process is pretty straightforward and the scientific community has reached a unanimous consensus on their origin. For these objects, starting from metric sized rocks, these building blocks aggregate into bigger and bigger objects, until they reach the stage of planetesimals, having a radius ~ 1000 km. These big planetoids collide and then merge, until the final phase of planet is reached.
There is a different story for the gas giants. Two models have been proposed, the core accretion and gravitational instability. However, in the case of the solar system, the scientific community strongly agrees that they formed via the core accretion where an initial nucleus of about 10 M_E is formed in a similar way of the terrestrial planet. After reaching this value, it is massive enough to start attracting the gas residual of the circumstellar disk until it reaches its final mass and size (Matsuo et al. 2007).
The system, therefore the protoplanetary disk, can be considered isolated, at least from a point of view of the mass. There certainly are far energy sources, such as X-rays and UV photons which definitely played a role into the planets' growth. But, the mass orbiting around the young Sun was not changing (or, at least, it could be neglected).
Concerning moons, there is a whole new story behind it. First of all, the satellites are thought to have been formed in several different ways. An easy example is the capture, which is the case of the martian moons Phobos and Deimos. They were very likely asteroids belonging to the main asteroid belt which were captured by Mars at a latter stage. Another case is the Moon itself, among the biggest satellites of the solar system. It was formed after the debris which followed a huge impact between the young and still partially molten Earth and a Mars-sized planetoid. Other moons are thought to have been formed in the so-called CPDs, effectively mini-stellar systems which are originated around gas giants, in a very similar shape to the circumsolar disk (Serman 2018). This is probably the case for the moons of Jupiter and Saturn, excluding the irregular satellites, as explained in detail in section 1.2.
Therefore, it is not possible to treat this disk as a classical PPD because of, as a first example, the isolation. While the circumsolar disk had little interference from outside, mainly due to high energy fluxes (cosmic rays, etc) located far away, the CPD was placed close to an extremely strong energy source: the Sun. The young star was already there when the gas giants were forming, and it had a strong impact on this process, almost certainly on the moons' formation as well. Another parameter which may have had a strong impact on the moons formation is the mass of the CPD. As it was contained inside the PPD, a connection may have existed between them, resulting in a certain mass flow during its existence, either positive or negative. It may have also just been isolated, due to the too wide gap

opened by the planet, which would have cut off the CPD from the rest. However,it is argued that the two disks were actually coupled and that an actual mass flow existed (Canup and Ward 2002, Miguel and Ida 2016).
It will be necessary to be careful in handling the various parameters offered by ProDiMo. In the rest of the chapter some assumptions will be explained, supported by previous works. As the project will go on, certain models will be discussed case by case, due to the complicated nature of some particular changes.

3.2. Defining a young Jupiter

The first problem faced was to determine the Spectral Energy Distribution of Jupiter at the time its moons formed. The energy coming from the young planet at the center of the disk is the most important factor influencing the composition and structure of the disk, according to Szulágyi 2017. It will be important to correctly determine its supply to match the actual composition of the moons with the result of the simulations.
The first aim is to define the SED of a young Jupiter, and then to implement it into ProDiMo. The program takes the stellar characteristics from the PHOENIX catalogue (Baron et al. 2003). This library of stars contains hundreds of stellar spectra where three degrees of freedom can vary; nominally, the temperature, the surface gravity and the metallicity.
In the file *Parameter.in* the user has the possibility to declare however different parameters: absolute temperature and relative luminosity and mass with the respect to the Sun. Based on the inputs, ProDiMo calculates itself which PHOENIX model best fits with the desired star.
The first problem which arose was the lower boundary of the model. In fact, as stated in section 2.2.1, it could accommodate stars down to 3000 K, which corresponds to an average red dwarf. This is way more than the temperature that a young Jupiter could have during its accretion phase. On a later stage, the authors decided to add many more spectra of low temperature, down to 1000 K. This corresponds to the temperature of a (relatively cool) brown dwarf, see Chabrier et al. 2000 for more references. This borderline class of stars has by definition a mass between 13 and 80 M_J. These values are so low that those stars are not even able to sustain the hydrogen nuclear fusion. They are thought to produce a weak energy they emit from the fusion of deuterium and lithium. The classical temperature of a brown dwarf is about 1400 K, but this temperature can be as cold as 500 K, in some cases (Chabrier et al. 2000).
However, Jupiter itself cannot be considered to be a star. Its mass is only 0.001 $M_\odot$ and therefore its internal pressure is not even enough to trigger the fusion of deuterium. Jupiter, together with a bunch of similar objects having masses smaller than 13 M_J, are also called sub-brown dwarfs. This class of object is borderline among the planets and the stars. Their effective surface temperature is of the order of 400 K. Jupiter is even less, it is barely above 160 K at 1 bar. In fact, being a gas giant, it is hard to define where the surface exactly lays - 1 bar is being commonly used as reference point.
This means that the PHOENIX model is not suitable for the purpose of this thesis. However, the very low temperatures are attributed to the Jupiter that can be observed now.The Jupiter present during the formation of the moons was a young still accreting planet, way hotter and larger in size than today's.
Recently a younger "twin" of Jupiter has been detected, called 51 Eri b (Rajan et al. 2017). It is almost 30 pc from the solar system orbiting around a red dwarf star. It is supposed to be 20 million years old which is, according to many theories (Canup and Ward 2002 and Ronnet, Mousis, and Vernazza 2017), around the time when the Galilean moons were forming. As a first approximation, it will used the SED of objects resembling Eri b to mimic the young Jupiter SED. A comparison of the ProDiMo result and Eri b can be seen in figure 3.4. Rajan et al. 2017 affirm that the temperature of Eri b is about 750 K and its mass is around 3-4 M_J.
The very young Jupiter, at about 10 million years old, was perhaps even hotter, around 1300 K according to Mosqueira and Estrada 2003. Other studies suggest that it was probably lower than 1000 K, as indicated in Miguel and Ida 2016 and Canup and Ward 2002.
Very recently, another paper has pointed out that the temperature of the planet could actually be way higher that previously thought, even up to 10000 K (Szulágyi 2017). Cilibrasi et al. 2018 have used the same models of the aforementioned paper, however taking into account the lowest possible temperature, 2000 K. For now, this greater number will not be considered as the classical models of young gas giants state a temperature around 700 K.

To determine the parameters needed in ProDiMo the following procedure has been followed. From Burrows et al. 1997, the evolution of the planets and stars luminosities with age have been estimated. This is shown in the two plots below, figure 3.1 and 3.2. We here consider a mass of 0.001 $M_{\odot} \sim 1\ M_J$. A first initial guess for the age is 10 million (10^7) years, for two reasons: it is an estimated age of Jupiter in which the moons may have formed, according to many papers (Miguel and Ida 2016, Mosqueira and Estrada 2003 and Canup and Ward 2002). Secondly, the age of Eri b, the twin of Jupiter, is 20 millions old. Therefore, following the line, the initial luminosity ratio between the young Jupiter and the Sun is 10^{-5}.
Figure 3.2 shows the evolution of the gravity surface as a function of T_{eff}, for different stars and planets masses and ages. Following the grey line of 10^7 years, the T_{eff} should be around 750 K. However, given the minimum value that ProDiMo allows, the chosen temperature is 1000 K. The gravity surface of the young Jupiter at the age of 10 Myr is about 3 $cm \cdot s^{-2}$.
However, ProDiMo does not directly require the gravity surface. This parameter is automatically computed by the declared temperature, mass and luminosity of the central object.

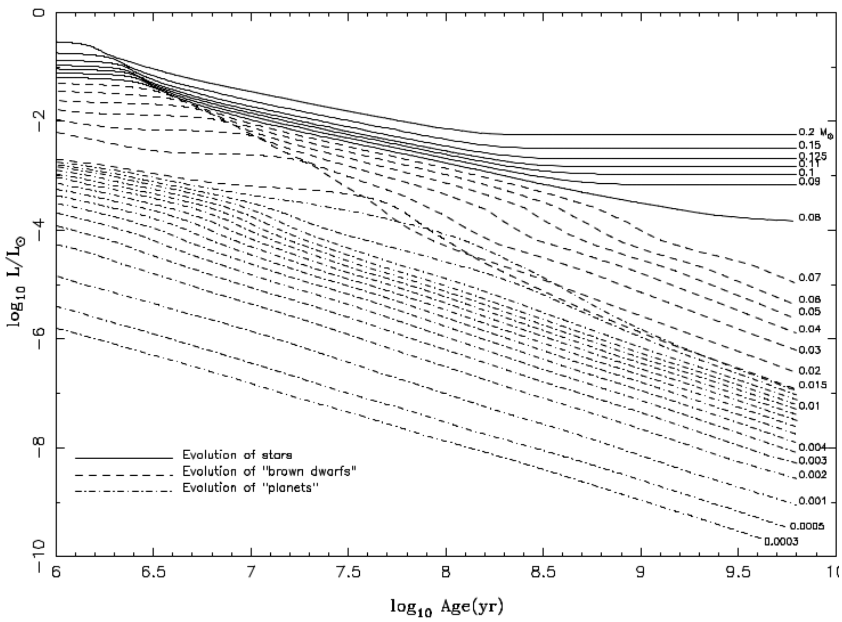

Figure 3.1: Evolutionary path of several low mass objects, such as planets and brown dwarfs, indicated by the ratio of their mass and the solar mass. The y-axis represents the logarithmic ratio of the luminosity and the x-axis the logarithmic scale of age (Myr) (Burrows et al. 1997).

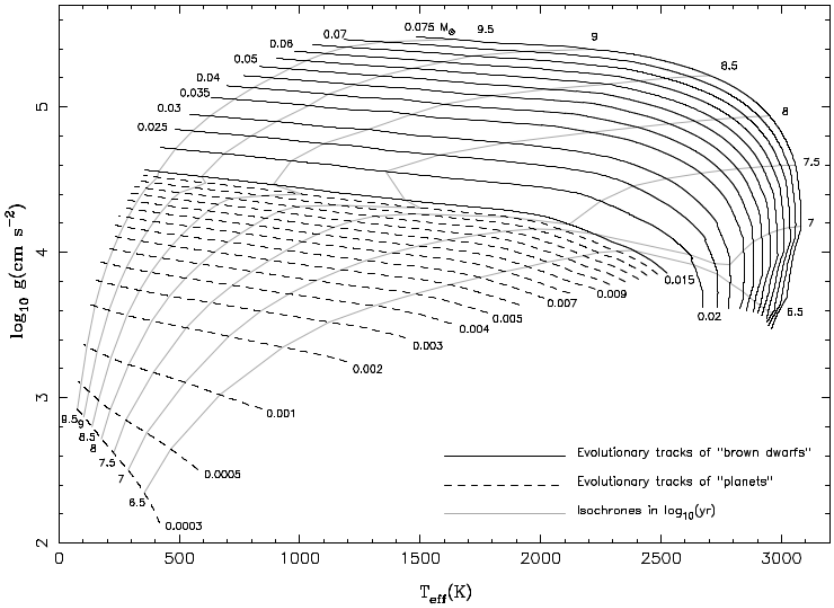

Figure 3.2: Family of curves where the grey lines indicate the age (in Myr) and the black ones indicate the masses in $M_{\odot}$. The x-axis has the effective temperature (K) and the y-axis the log of the gravity surface (cm/s^2) (Burrows et al. 1997).

3.2.1. Implementing the young Jupiter in ProDiMo

As a first step, we will consider a young Jupiter having a temperature of 1000K so that we can used the lowest effective temperature provided in the DRIFT-PHOENIX SEDs.
The first parameters given to ProDiMo are shown in table 3.1.

Table 3.1: A table summarizing the parameters related to the young Jupiter which are initially implemented in ProDiMo.

Parameter	Value	Unit
Mass	0.001	$[M_{\odot}]$
T_{eff}	1000	[K]
Luminosity	10^{-5}	$[L_{\odot}]$

The SED spectrum of the young Jupiter is obtained by choosing the PHOENIX data, as reported in picture 3.3. It is very different from a classical young star SED. The typical black body shape is very compressed and the peaking region is not clear.
As comparison, the SED of 51 Eridani b and a zoom of the prodimopy result of 3.3 are shown in figure 3.4. The units are identical, as well as the boundary conditions: distance at 29.4 pc and the wavelength considered in the interval 0.2-5 μm. The chosen distance is the same than the one of the young gas giants 51 Eridani b shown below.
It can be appreciated that the flux obtained is of the same order of magnitude than the one seen in the observations, which is about $10^{-16} W/m^2$, with a factor 2 difference between the PHOENIX model and the observational data. This may be explained by the chosen temperature of 1000 K for the model, which is probably a too large value for the young Jupiter. Indeed Eri b is thought to be around 605-713 K (Rajan et al. 2017).
The y-axis indicates the flux measured in $10^{-16} \cdot W/m^2$. In ProDiMo the flux is usually expressed in $erg/cm^2/s$ which is, by definition, equal to 1000 W/m^2. Hence, the peaks shown in figure 3.4 have been converted into W/m^2 dividing by 1000. However, a large portion is missing in this observed spectral energy distribution, as no measurements are reported above 2.5 μm, which is where the maximum of the flux is located.

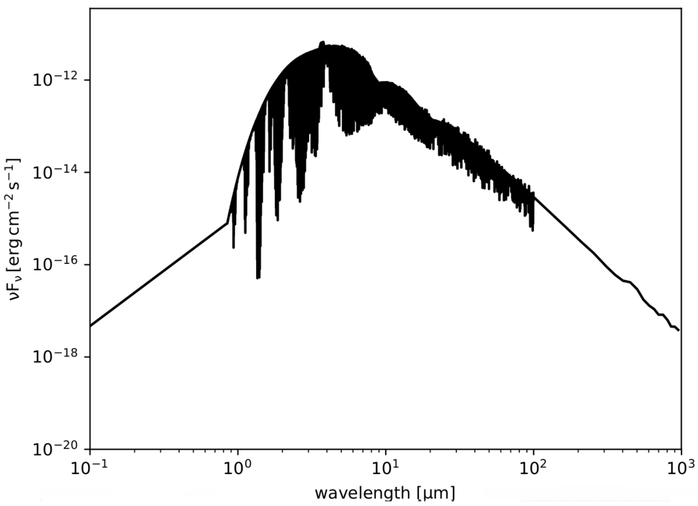

Figure 3.3: Prodimopy plot showing the first modeled Spectral Energy Distribution of a young Jupiter in black, obtained by the PHOENIX model, in black. It is set to be observed at a distance of 29.4 pc.

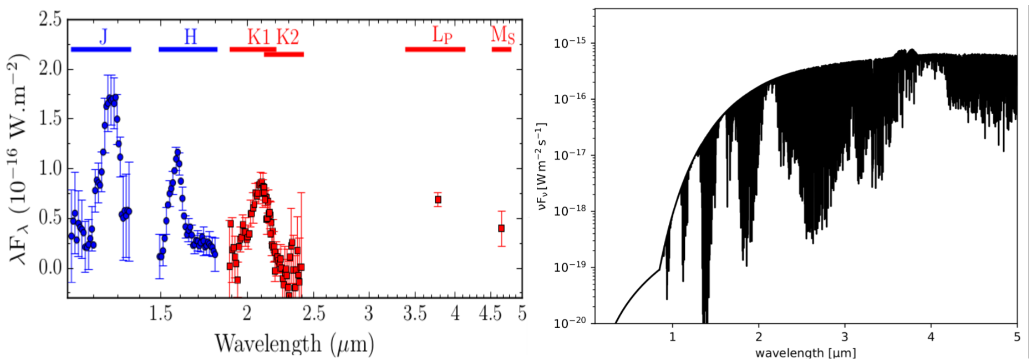

Figure 3.4: On the left, the SED of the directly imaged exoplanet 51 Eri b (Rajan et al. 2017). On the right, a zoom of the spectrum of the PHOENIX young Jupiter in the wavelength region between 0.1 and 5 μm, in order to make a comparison.

3.2.2. Modelled SEDs of young gas giants

In another study from Fortney et al. 2008, SED of stars and exoplanets with T_{eff} < 1400 K have been modelled. The figures 3.5 and 3.6 show the SED determined in this paper. With such models, the SED of low mass objects can be determined. The emission between 1 and 6 micron differs from what is shown from a PHOENIX spectra because of several reasons. For example, the different temperature used. These models can also follow the evolution of the three modelled gas giants, indicated by the different colours. The first figure is an estimation of the fluxes observed at an age of 10 Myr, while the second is the result at 80 Myr. As expected, as the young planets age, their total fluxes diminish, about one order of magnitude after 70 Myr. The figures show three different initial spectra for the young Jupiter with three different lines, even though two consider the same model, but with a five times higher metallicity for one of them.

The model considered to be the closest to a young Jupiter is the dark blue line, which represents the core accretion start, the most credited Jupiter formation theory. According to this process, the gas giants core accrete in a similar manner than the terrestrial planets, until a threshold value of about 10 M_E is reached. Afterwards, the gravitational field originated by the core is strong enough to start attracting the lighter gas and dust particles present in the protoplanetary disk. Being mostly hydrogen and helium, these will form the extremely thick atmosphere of the gas giants, and they can in principle be very massive. Jupiter itself is about $0.001\ M_\odot$ and recent estimations state that 1% of the sun mass is enough to start fusing the deuterium, therefore becoming a brown dwarf. In such a scenario, Jupiter was not too far from being the second star of the solar system.
The other theory is called gravitational instability (also known as hot start in Fortney et al. 2008), and is thought to be a similar process than star formation. In fact, Jupiter and other gas giants would have

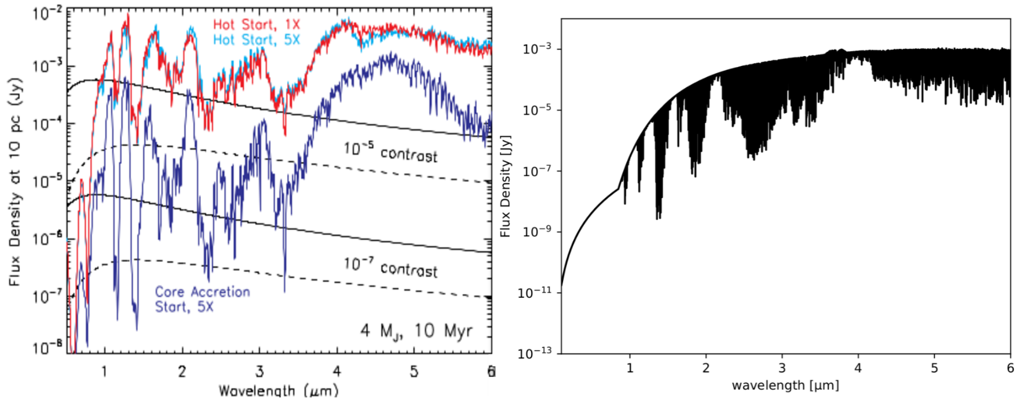

Figure 3.5: On the left, flux density at 10 pc for 4 $M_J$objects at an age of 10 Myr. In red is a hot start evolution model with solar metallicity at 1000 K. In light blue is this same model with 5× solar metallicity, for comparison. In dark blue is a 600 K model that uses the core-accretion initial condition and 5× solar metallicity. Over-plotted in black are 10^{-5} and 10^{-7} contrast ratios relative to two blackbody stars. The two solid curves are for a Sun-like 5770 K star and the dashed curves are for an M2V-like 3600 K star (Fortney et al. 2008). On the right, flux density at 10 pc for the young Jupiter, as described at the beginning of this section.

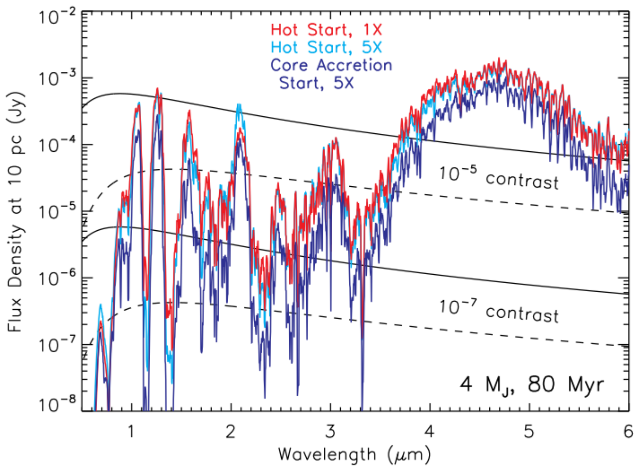

Figure 3.6: Flux density at 10 pc for 4 M_J objects at an age of 80 Myr. The colours indicate the same models of 3.5 (Fortney et al. 2008). The decrease of the flux over the 70 million years is clearly appreciable

formed from regions with higher densities in the PPD. They would have caused gravitational instabilities within the disk, which would have later altered its structure and eventually underwent a gravitational collapse which led to the formation of the planets. Therefore, the giants could have been formed directly from the PPD orbiting around the young Sun. There are however two constraints to be taken into account, nominally the mass of the disk, which had to be large enough (the so called Jeans mass), and the temperature, which also had to be cool enough. In fact, gravitational instabilities happen more frequently as the temperature goes down (Matsuo et al. 2007). This was also better described in the literature study, where it is shown how the Jeans equation links a decreasing temperature with an increasing mass (Serman 2018).
According to the last estimations (Matsuo et al. 2007), the temperature in the young solar system was too high to allow such a process and hence the core accretion model is so far considered to be the most realistic. However, it has to be stated that roughly 10% of the observed gas giant exoplanets have thought to be formed via this last mentioned process (Matsuo et al. 2007).
If the gravitational instability were considered then the flux density would be on average 1 or 2 order of magnitude stronger. This could have an important impact on the CP structure and composition and therefore is a parameter which has to be treated very carefully. For example, the effective temperature of a 1 M_J planet modelled with core accretion would be 672.5 K, compared to the 900.3 K forecast for

the hot start scenario (Fortney et al. 2008).
As comparison, the previous stellar model of figure 3.3 from ProDiMo has been recalculated at a distance of 10 pc and converted into Jansky, as used in Fortney et al. 2008. The result is the right plot in figure 3.5. The PHOENIX SED has a maximum flux around 10^{-2} Jy, at 5 microns while the SED determined by Fortney et al. 2008 has a maximum flux of 10^{-3} Jy at 5 microns.
This is shown in figure 3.5, simulated at the age of 10 million years, which is a very reasonable time for the formation of the Galilean moons and is also consistent with the choice made using picture 3.2, the plots are similar, but in this case again ProDiMo yielded slightly larger fluxes. That is because the SED from the PHOENIX model is too warm and, hence, the produced flux is too high. Future attempts may include the realization of a proper own SED. PHOENIX does not allow to go below 1000 K and, as stated previously, lower temperatures may be needed to have better and more correct simulations.

3.3. The properties of the disk

The second next big step to define the boundary conditions is to implement correctly the circumplanetary disk. So far, it is not clear what the dimensions of the CPD were.
The vast majority of simulations performed so far when trying to reconstruct the formation process of the satellites were dynamical. A varying quantity of particles, for example 10 thousands, were let free to move and aggregate for a certain period of time. The major results have already been discussed in chapter 1. For example, the n-bodies simulations run by Ronnet, Mousis, and Vernazza 2017 or Miguel and Ida 2016. But, in general, those authors needed different parameters than a ProDiMo simulation. For example, the temperature profile of the CPD. For the aforementioned simulations, the temperature was an important parameter for the movement of the particles. In the thermo-chemical simulations run with ProDiMo, the temperature profile is also a result of the balance between the heating and cooling processes acting in the disk. It is not given as input, as Miguel and Ida 2016, Ronnet, Mousis, and Vernazza 2017 did. What ProDiMo requires is, for example, the disk mass. Another parameter is the dust to gas ratio, as explained in section 3.1.

3.3.1. The sizes

Little is known about the sizes of the circumjovian disk. For simplicity, its shape is usually considered to be circular (Mosqueira and Estrada 2003). This is also what ProDiMo does, as the same approximation also holds for PPDs. The program allows to select the inner and the outer radius, which are the physical limits of the disk. From the literature, different dimensions have been used. In Miguel and Ida 2016 the chosen inner and outer radius are respectively 2.25 and 150 R_J while in Canup and Ward 2002 2 and 150 R_J are the boundaries. The inner limit is given by the proximity to the young Jupiter, where the gravity pull directed towards the planet is too strong, and the outer one corresponds to 0.2 Hill radius for Jupiter. Historically, the external limit was considered to be Callisto's orbit, the outermost moon. However, the work of Mosqueira and Estrada 2003, advocated that the limit should be pushed more external, up to the aforementioned 150 R_J.

3.3.2. The mass

Another puzzle concerns the total mass of the disk. This has been treated in essentially two different ways in the literature. As described by Mosqueira and Estrada 2003, the *minimum mass* disk simply calculates the sum of the total mass of satellites and considers a perfect accretion, where the starting mass is indeed the total mass which will be ultimately delivered into the satellites. This amounts to about 10^{-4} M_J. The same approach has also been used by Miguel and Ida 2016.
Another option is to use a so-called *gas starved* disk, in which it is assumed that the initial mass was about $\sim 10^{-2}/10^{-3}$ the final satellites' mass (Konrod and Makalkin 2017). The CPD model then should also incorporate a mass inflow into the disk in order to accumulate enough solid material for the moons to accrete to the current sizes. This model was first proposed by Canup and Ward 2002 and has been used by many authors, such as Ronnet, Mousis, and Vernazza 2017 and Heller, Marleau, and Pudritz 2015. For now, to keep the simulation at a simple level, the minimum mass model has been chosen, therefore without including any mass inflow rate to the CPD.
A summary of the parameters used in the simulations is indicated below in table 3.2.

Table 3.2: A table summarizing some of the parameters related to the CPD which are initially implemented in ProDiMo.

Parameter	**Value**	**Unit**
CPD mass	$2 \cdot 10^{-2}$	$[M_J]$
Inner radius	2.25	$[R_J]$
External radius	150	$[R_J]$

3.3.3. The composition

Once the disk size and general properties are defined, it is necessary to also estimates its initial composition. A key parameter is the dust to gas ratio. The chosen value corresponds to 0.01, as also used in Miguel and Ida 2016, Canup and Ward 2002 and Szulágyi et al. 2016. This is also the typical ratio found in the interstellar medium, and hence the preferred value for these kind of simulations, given the close relation between the ISM and the CPD. However, as explained in Miguel and Ida 2016, the circumjovian disk is not "alone", like the the classical circumsolar disk. In this sense, it may present a different ratio. In the paper certain simulations have been performed with a ratio of 0.1. That is because the CPD could be supplied of solids through the ablation of captured 100km-sized bodies orbiting around the Sun. This would greatly enhance the presence of solids, up to a factor of 10, and is consistent with the latest solid traces observed in the Jovian atmosphere (Mosqueira and Estrada 2003).
ProDiMo uses a power law distribution for the particles' sizes. In Mosqueira and Estrada 2003, the power law exponent was 3.5, which is also the typical value for the ISM. The dust size distribution can be described as follow:

$$dn_{gr}(a) = Cn_H a^{-3.5} da, \; a_{min} < a < a_{max} \tag{3.1}$$

where a_{min} and a_{max} represent respectively the minimum and maximum particle size, n_H is the number density of H nuclei, n_{gr} is the grain density of grains with sizes a and C is a constant, which is $10^{-25.11}$ $cm^{2.5}$ for silicates and $10^{-25.13}$ $cm^{2.5}$ for graphite (Mathis, Rumpl, and Nordsieck 1977).
The minimum and maximum particle sizes are the next puzzle. Again, for simplicity, as initial guesses the value typical of the solar nebula (i.e., the circumsolar disk) have been used. From the standard of ProDiMo the values are as follow in table 3.3.

Table 3.3: A second table summarizing some of the parameters related to the CPD which are initially implemented in ProDiMo.

Parameter	**Value**	**Unit**
Dust to gas ratio	0.01	[-]
Minimum size particle	0.05	$[\mu m]$
Maximum size particle	3000	$[\mu m]$

3.4. Results of the first simulation (model F1)

The disk turned out to be extremely dense and optically thick, compared to a classical PPD. However, this is consistent with the expectations, as also calculated in Miguel and Ida 2016, who used our same minimum mass model. A comparison between with this paper's gravity density profile is shown in figure 3.7. Our profile is more curved compared to the other, but this depends on the power law distribution. While the surface gravity density showed appreciable results, the temperature profile had very unexpected values. It was dropping below 100K already at about 10 R_J. As comparison, the temperature profile of Ronnet, Mousis, and Vernazza 2017 is shown in the right picture of 3.8, while the output of ProDiMo is on the left.
This results in a snowline for H_2O which is very close to the planet, at 3 R_J. The CPD is completely frozen. This differs with the work carried out by Miguel and Ida 2016, where the snowline is located between Europa and Ganymede, between 10 and 15 R_J. This value was chosen in order to explain the water content of Europa. With ProDiMo' results, we are getting a similar amount of water ice on all the moons.
The figure 3.9 is a classical output of ProDiMo, processed through prodimopy. It represents the abundance of water ice. The yellow area indicates a massive abundance, even in the inner orbit of Io's.

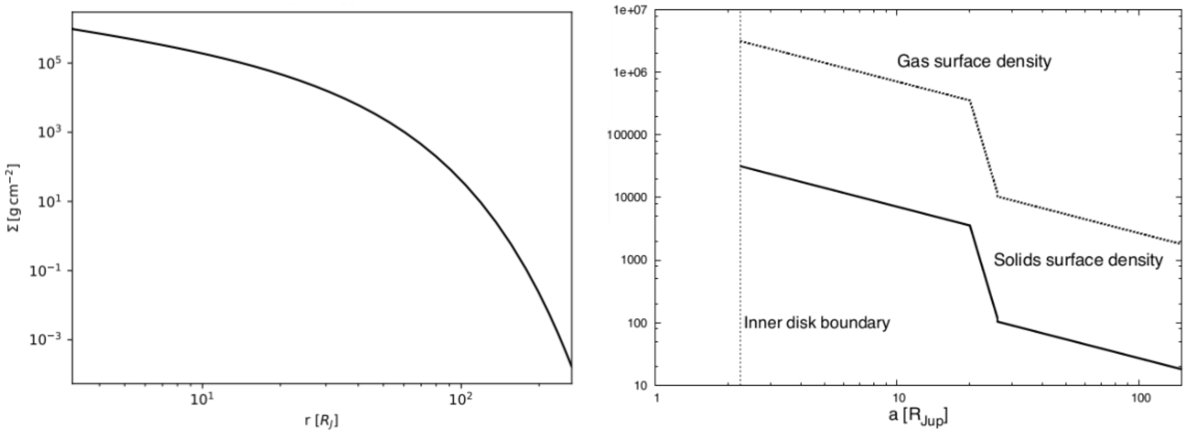

Figure 3.7: Comparison between the surface gravity densities obtained by ProDiMo and Miguel and Ida 2016. The various lines indicates different models. As described, the dashed line Both these simulations have used the minimum mass disk.

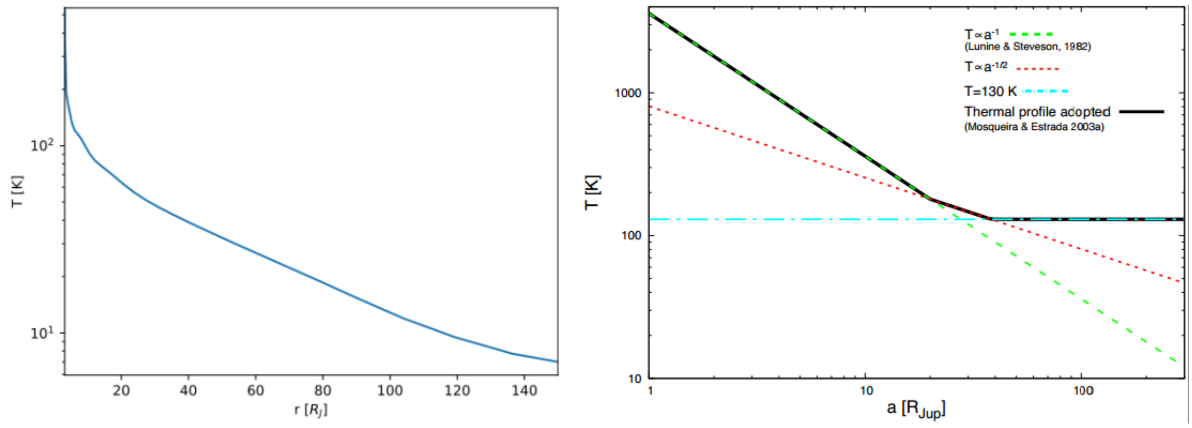

Figure 3.8: Temperature profile of the circumjovian disk, at the level of the radial midplane. The x-axis indicates the radius and the y-axis the temperature. The plot on the left is the ProDiMo output, while the one on the right is taken from Miguel and Ida 2016. The colours indicate the different sources for their profile, which is defined by the black line.

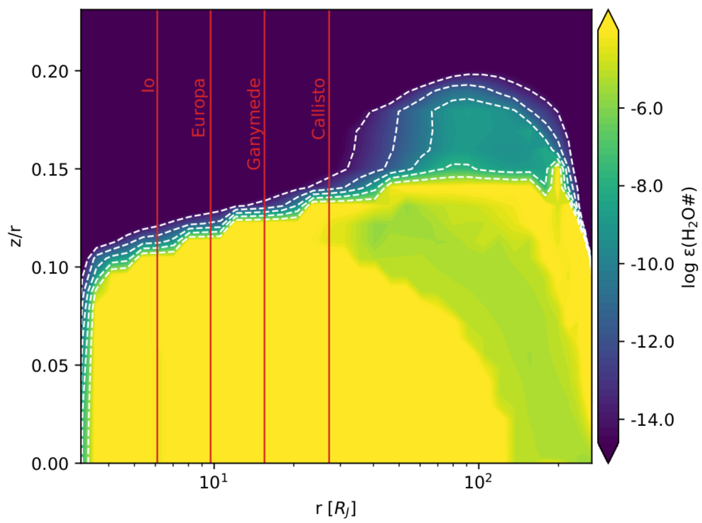

Figure 3.9: Abundance of the water ice in model F1. The present locations of the moons are indicated by the red lines.

3.5. First conclusions

So far, the results from ProDiMo differs quite a lot from the the simulations of Miguel and Ida 2016. Our work has resulted in a completely frozen CPD. The H_2O snowline is by now located at 3 R_J, whereas the closest satellite, Io, is located about $\sim$ 6 R_J.
The reason for this very low temperature turned is fairly simple. The disk is very dense, around 2–3 order of magnitudes higher than classical PPDs. Therefore, the energy contribution of the young Jupiter alone is not enough to heat up the gas and dust contained in the CPD.
We can read these results in many different ways. In principle, the idea would be to find something similar to Ronnet, Mousis, and Vernazza 2017

- The results are correct, and all the young Galilean satellites were rich in water, including Io and Europa. This water would had then been lost due to various reasons (tidal heating on Io, for example).
- The minimum mass model is not correct and the gas starved disk proposed by Canup and Ward 2002 should be investigated. (see section 4.3)
- The contribution of the Sun is not yet considered. Since it was young, it was more powerful that it is today. But still it could represent a significant source of energy, maybe more important than the young Jupiter. (see section 4.5)
- With respect to the above point, the migration of the planets is also not considered. It is possible that Jupiter was closer to the Sun at that time, enhancing the solar contribution. (see section 4.6)
- The viscous heating is not considered yet. As Canup and Ward 2002 suggests, this effect was likely the dominating process, and its inclusion would result in a higher temperature for the whole disk. (see section 4.2)
- It is possible that the moons were forming while the young Jupiter was still accreting. Hence, additional heat would have been transferred by this process, resulting again in a warmer disk. (see section 4.7)
- Similarly to the above point, the PPD could have contributed to generate a "background" heating all around the CPD. This can be simulated imposing a general background temperature in ProDiMo. (see section 4.4)

There is a list of aspects which have not been considered yet. Some of these ideas will be explored in the next chapter, in the attempt to better understand what was going during the formation of the Galilean satellites. The model emerged in these last sections will be called model F1 and will be used as a fiducial set of values in the following chapter 4.

4

Alternative CPD simulations: establishing the heating sources of the disk

After the first round of simulations, many questions are still unanswered and new ones emerged. In this chapter, the focus will be on trying to solve the previously mentioned points of discussion. New parameters and effects will be tested, assessing some interesting factors such as the effect of the Sun or the viscous heating.

4.1. First fiducial model (model F1)

In chapter 3 the first attempt to describe the early Jovian system has been carried out. As emerged the obtained CPD presents an the extremely low temperature which would result in a moon system completely frozen, which differs from the previous theories where the snowline is located around Europa. As indicated in the last section of the previous chapter, many new paths will be attempted. For the moment, the current fiducial model is defined as set in chapter 3. The key characteristics are presented below, with an aside annotation indicating the section in which they will be further analyzed.

Table 4.1: Most significant parameters of model F1. The fourth column indicates the section of the current chapter it which this parameter will be discussed. The last column indicates the names of the new models related to the changed parameters.

Parameter	Value in model F1	Unit	Section	Model name
Luminosity of Jupiter	10^{-5}	$[L_\odot]$	Sec. 4.7	Model WBJ
T_{eff}	1000	[K]	Sec. 4.7	Model WBJ
CHI_ISM	1	[-]	Sec. 4.5 & 4.6	Model Sun & GT
CPD mass	$2 \cdot 10^{-2}$	$[M_J]$	Sec. 4.3	Model GS
Mdot	Not used	$[M_J/\text{yr}]$	Sec. 4.2 & 4.3	Model VH & GS
Dust to gas ratio	0.01	[-]	Sec. 4.3	Model GS
Background Temperature	2.7	[K]	Sec. 4.4	Model BH

4.2. The viscous heating (model VH)

The $Mdot$ parameter enables the viscous heating in the CPD, as explained in section 2.2.4. However, it is not immediate to select the proper value for the mass accretion rate of the CPD. Ronnet, Mousis, and Vernazza 2017 suggests that a 10^{-7} M_J/yr, while Canup and Ward 2002 affirmed that it was much higher, up to $10^{-4} - 10^{-6}$ M_J/yr, however also suggesting a gas starved disk. Heller, Marleau, and Pudritz 2015, on the other hand, consider a smalller value, $\sim 8 \cdot 10^{-8}$ M_J/yr. The following figure 4.1 shows how the viscous heating is now the dominating process in the central part of the disk, including the midplane region where the moons are forming.

Table 4.2: Added parameter Mdot, together with its value, in order to consider the viscous heating (model VH).

Parameter	**Model F1**	**Model VH**	**Unit**
Mdot	Not used	10^{-7}	$[M_J/\text{yr}]$

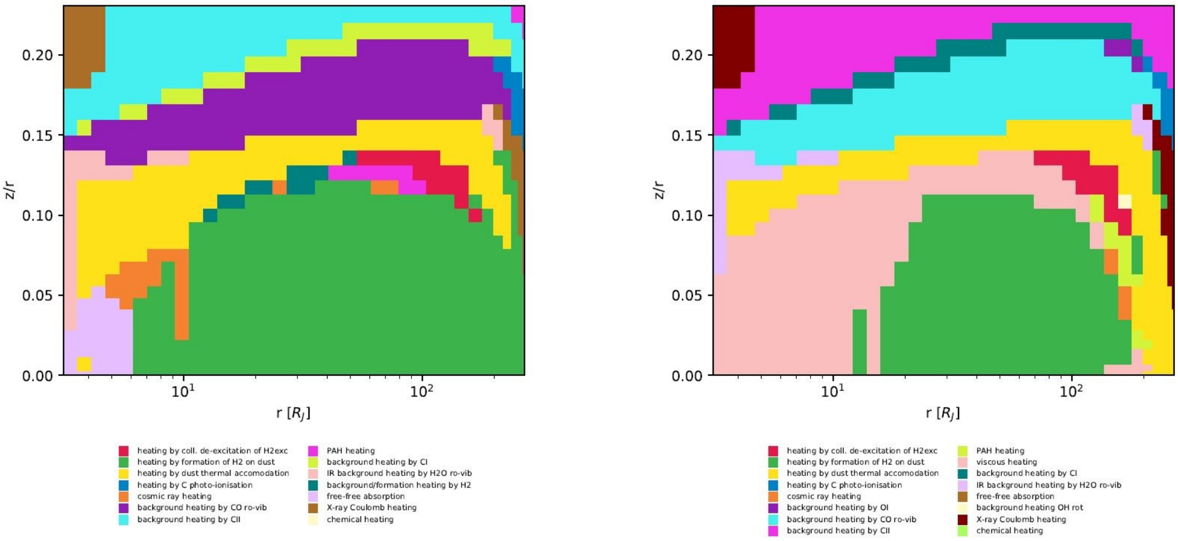

Figure 4.1: Contour plot indicating the major heating processes in any discrete interval of the CPD. Each square indicates a region of the CPD, having the radius in the x-axis and the ratio between the height and the radius itself in the y-axis. The colour indicates, according to the legend, the dominating heating source in that particular sector of the CPD. On the left, model F1. On the right, model VH. The effect of the viscous heating is mostly perceived in the inner part, indicated by the pink colour.

Nonetheless, this does not affect the temperature profile of the region presenetly occupied by the moons in the CPD. Figure 4.2 compares the dust temperatures of the two different simulations with and without the viscous heating and a sgnficant different is noticeable around 40 R_J.

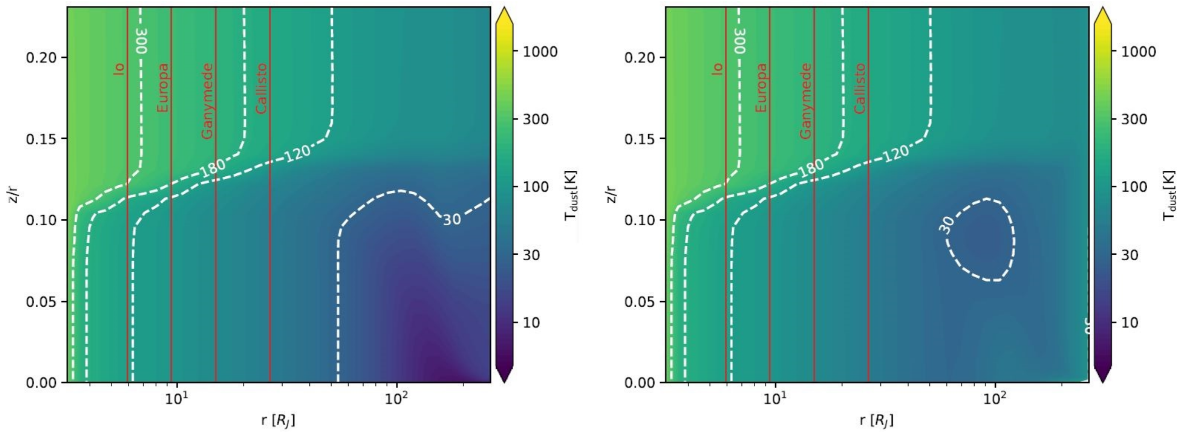

Figure 4.2: Comparison of the contour plots showing the dust temperature with (right, model VH) and without (left, model F1) the Mdot based viscous heating.

4.3. Gas starved CPD (model GS)

Following Canup and Ward 2002, it has been attempted to simulate a so called gas starved CPD. In this case, the mass considered is $10^{-4}\ M_J$, as an averaged value as suggested by Konrod and Makalkin 2017. The mass inflow Mdot is also considered and kept to $10^{-7}\ M_J$/yr as backed by Canup and Ward 2002 and Ronnet, Mousis, and Vernazza 2017.

Table 4.3: Modified parameters for model GS.

Parameter	Model F1	Model GS	Unit
Mdot	Not used	10^{-7}	$[M_J/\text{yr}]$
CPD mass	$2 \cdot 10^{-2}$	10^{-4}	$[M_J]$

In this case, the viscous heating is even more dominating than in model VH, as shown in figure 4.1. However, the CPD is still completely frozen, including the orbits occupied today by all the four moons. Figure 4.4 shows the dust temperature in models F1 and GT.

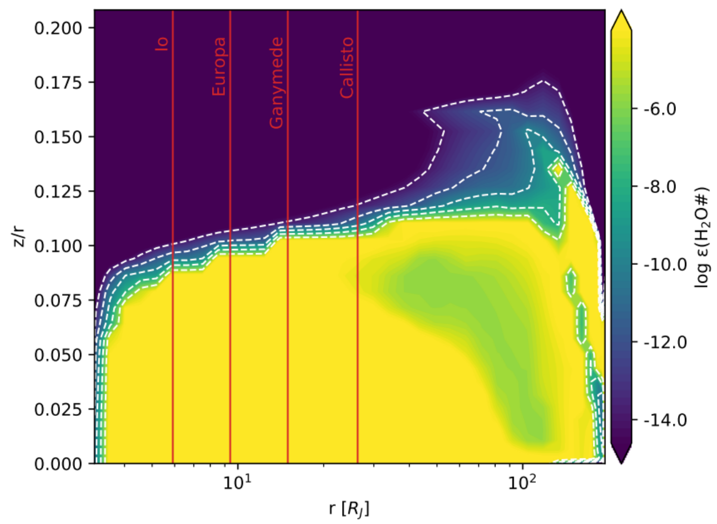

Figure 4.3: Water ice abundance in model GS. The locations of the moons are indicated by the red lines, together with their names.

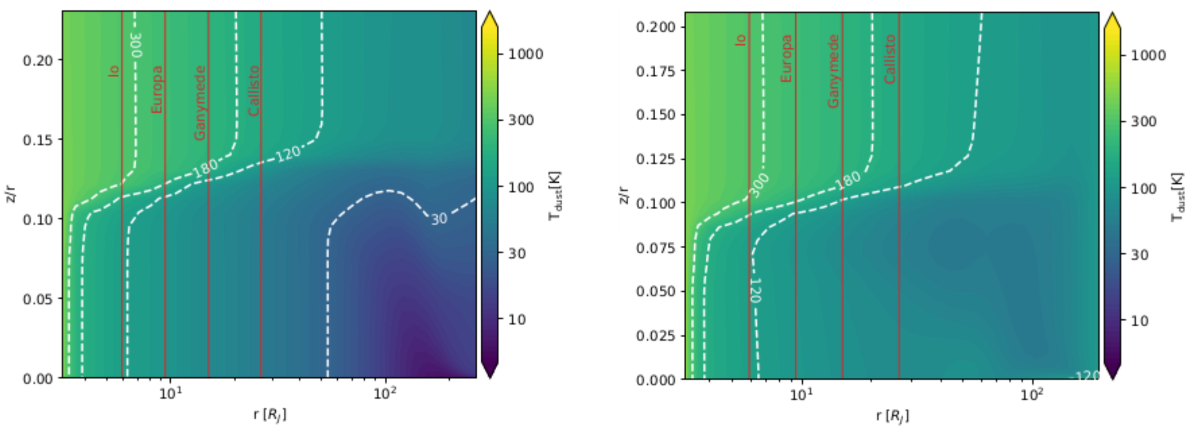

Figure 4.4: Contour plot of the dust temperature for the fiducial model F1 and model GS.

4.4. Background heating (model BH)

In section 2.2.5 the way in which ProDiMo simulates the cosmic microwave background radiation was presented. It was also mentioned that this option can be used to assess the behaviour of a disk forming in a warm environment. This applies very well to our simulations, as the CPD is located within a PPD and not in the open space. It is reasonable to consider a quite big background temperature, as also assumed by many previous authors, such as Miguel and Ida 2016 and Cilibrasi et al. 2018. The chosen value is 123 K, as later reported in table 4.4. This value corresponds to the solar nebula temperature equilibrium ($T_e \sim 280\sqrt{1AU/r}$, where r is 5.2 AU), as described by Mosqueira and Estrada 2003.

Table 4.4: The selected background temperature used, in accordance with the sources.

Parameter	Model F1	Model BH	Unit
Background Temperature	2.7	123	[K]

Figure 4.5 illustrates the effect of the background heating on the gas (above) and dust (below) temperatures. The background field heated mostly the outer part of the CPD, but its effect slightly moved outwards temperature contour lines in the satellites' zone.

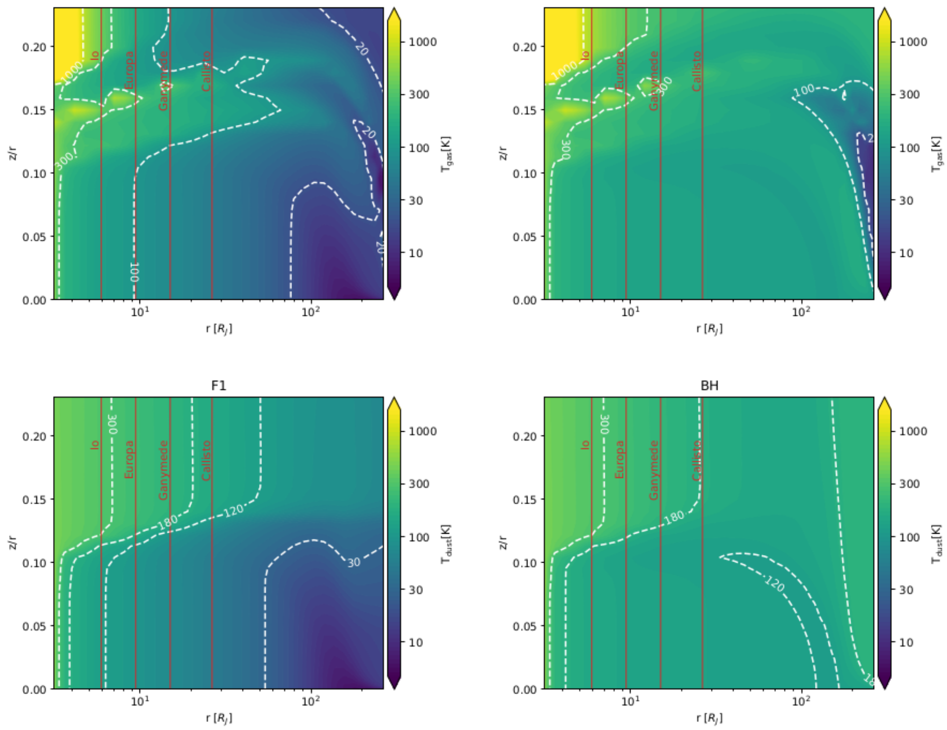

Figure 4.5: Contour plot of the dust and gas temperature obtained considering a background radiation field at T = 123 K (model BH), and model F1.

4.5. The contribution of the Sun (model Sun)

It is not easy to estimate the effect of the Sun for a ProDiMo simulation applied to a circumplanetary disk. In general, the software uses as main source of energy the star located in the centre of the disk. However, in this case, there would be another strong source located not very far away.
In general, to account for all external energy sources, nominally the interstellar radiation field, the software adds an homogeneous radiation field spread around the disk. It is the parameter CHI_ISM. Its default value is 1, which corresponds to the interstellar radiation field itself, determined to be $\simeq 4 \cdot 10^{-14} ergcm^{-3}$ (Habing 1968).
Rowan 2015 gave an interesting relation between the sun flux and χ is found, equation 4.1. The idea is to obtain an estimation of CHI_ISM influenced by the presence of the Sun.

$$\chi = \frac{(\nu u_\nu)_{1000Å}}{4 \cdot 10^{-14} ergcm^{-3}} \tag{4.1}$$

where ν indicates the frequency and u_ν its relative flux, at the wavelength of 1000 Å.
The best option to account for the Sun is to increase this value up to the estimated power irradiated to the CPD by the young star. A number of approximations have to be taken:

- CHI_ISM is set as a uniform background radiation. It is true that the Sun contribution came from the center of the solar system, and not from all around. However, due to the rotation of the materials in the PPD, as a first approximation we assume that the CPD was receiving a homogeneous contribution from the proto-Sun.
- Ribas et al. 2005 very well analyzed the evolution of the Sun irradiation and luminosity. They have come up with the fact that the Sun, at the estimated age of the Galilean satellites' formation, was irradiating way more energy. Its X-rays and UV emissions were, respectively, 100-1000 and 10-20 more energetic than the present time. As an average, the young Sun is considered 80 times more powerful than it is today (Ribas et al. 2005).
- Jupiter is nowadays located at 5 AU. The planetary migration theory suggests its location was possibly closer to the Sun during the satellites' formation. Heller, Marleau, and Pudritz 2015, on the other side, hypothesizes that in the so called Grand Track scenario Jupiter migrated from beyond 3.5 AU inwards down to 1.5 AU where it got locked into the resonance with Saturn. Later on, it migrated again backwards until its present location at about $\sim$ 5 AU. They argue that, if the moons would have formed at the minimal distance, the effect of the young Sun would have been way stronger and the H_2O should not have existed at all, resulting in completely dry moons. However, ice is present on certain moons and therefore they must have formed while Jupiter was far enough from the young Sun. The effect of the Sun at a closer distance will be assessed in section 4.6.

The solar radiation flux at the wavelength of 1000 Å is $\sim 10^{-3} erg/cm^2/s$ (Thompson 2018). It is now necessary to multiply it by the frequency to obtain a comparable number to put in equation 4.1.

$$\nu u_\nu = \nu \frac{c}{\lambda} \tag{4.2}$$

Putting all the numbers within the equations gives a final value for χ of roughly $8 \cdot 10^5$. Multiplying it by the factor of 100 hundreds obtained by Ribas et al. 2005, gives the final value of $8 \cdot 10^7$ which will be inserted in Parameter.in, instead of the default value of 1.0.
Adding this effect produces an extreme variation of the gas temperature in the outer and high disk, while the central region, closer to Jupiter, is less affected, similarly to the dust temperature. The CPD is generally a bit warmer, but the position of the snowline does not change much.

Table 4.5: Modified CHI_ISM compared with the previous default value, in order to assess the effect of the Sun.

Parameter	**Model F1**	**Model Sun**	**Unit**
CHI_ISM	1	$8 \cdot 10^5$	[-]

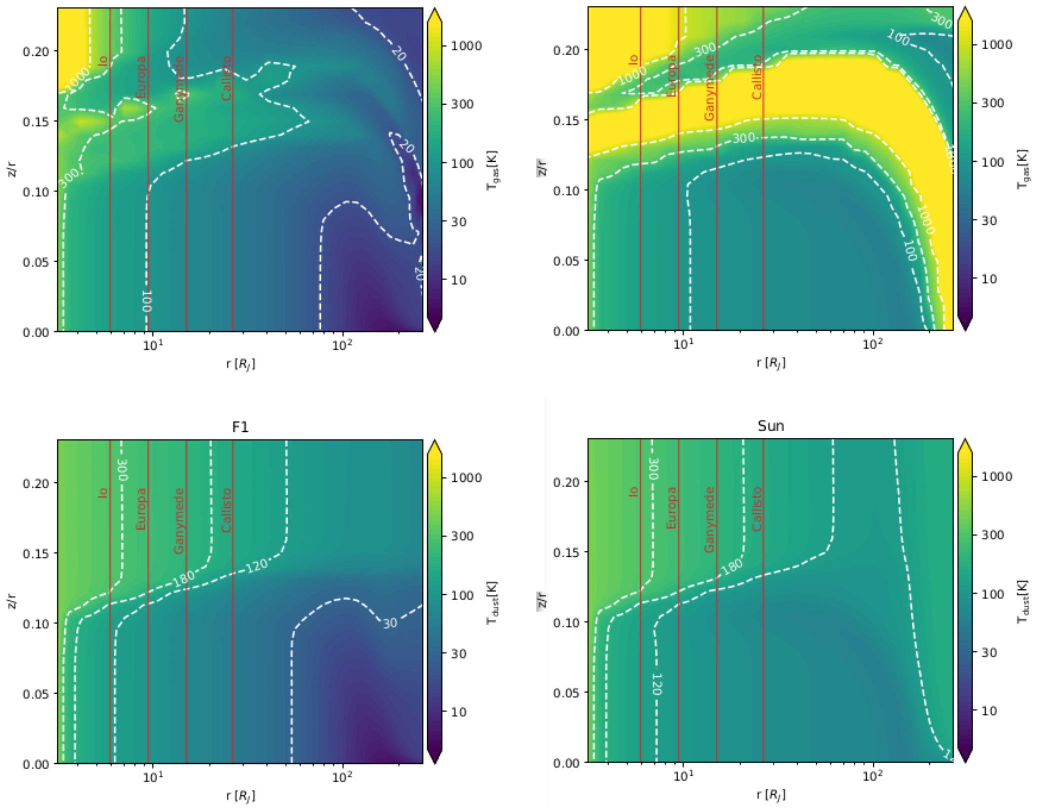

Figure 4.6: Contour plots of the dust and gas temperatures, comparing a simulation which includes the effect of the young Sun, on the right, and the fiducial model where it is not, on the left.

Model Sun results to be not so different from model BH (section 4.4). Since the PPD is mostly heated up by the young Sun, also the higher background temperature of the CPD would therefore mostly be due to the star. However, it can be noticed how the gas temperature is less affected in model BH. This is logical as in model BH only an infrared source is acting, which mostly affects the dust. On the other hand, in model Sun the mentioned CHI_ISM covers the whole spectrum, where the UV and X-ray regions play a major role in exciting the gas particles, especially when the dust is scarce (outer and higher regions).

4.6. Planetary migration effect (model GT)

To quickly assess the possible effect of the planetary migration, the worst case scenario (which means considering the closest approach of Jupiter to the Sun) has been considered. According to Heller, Marleau, and Pudritz 2015, Jupiter started from somewhere beyond 3.5 AU and moved inwards until 1 AU. Afterwards, it moved backwards until its actual location at $\approx$ 5 AU. Considering that the distance is one fifth of the reference value for model CHI, and that the energy flux is proportionally dependent to the squared inverse radius, we assume for CHI_ISM of $2 \cdot 10^7$, 25 times stronger than its effect at the distance of 5 AU.

Table 4.6: Modified CHI_ISM to take into account the migration of the young Jupiter

Parameter	Model Sun	Model GT	Unit
CHI_ISM	$8 \cdot 10^5$	$2 \cdot 10^7$	[-]

Heller, Marleau, and Pudritz 2015 have stated that the moons could not form at such a close distance to the Sun since it would have been too warm to have icy moons and assess that they formed in the last stage of the migration, close to the final 5 AU orbit. From ProDiMo as shown in figure 4.7, it appears that the Sun effect strongly affected the CPD, in accordance to Heller, Marleau, and Pudritz 2015. In this conditions it is still possible to form water ice in the inner moons (as utter proof of the extreme opacity of the CPD) but the outer regions are heavily affected and the moon Callisto would actually contain less ice than Io! As can be seen in figure 4.7 the abundance of the water ice starts to decrease around Callisto, while the three inner moons would have formed in a ice-rich environment. This is indeed not logical, at least according to the current theories. Figure 4.8 shows the dust temperature in models F1 and GT.

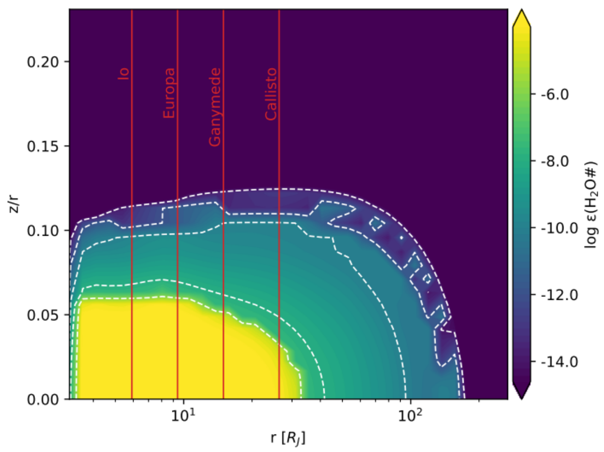

Figure 4.7: Contour plot of water ice abundance in model GT, which includes the effect of the young Sun at a distance of 1 AU.

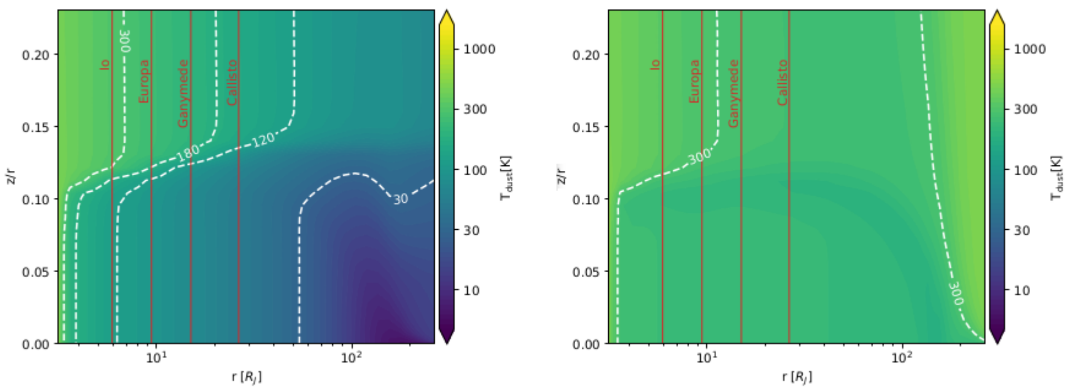

Figure 4.8: Contour plot of the dust temperature for the fiducial model F1 and model GT.

4.7. Considering a warmer and brighter Jupiter (models WBJ)

Cilibrasi et al. 2018 have been using a much warmer Jupiter for their own simulations than we did. The chosen surface temperature is 2000 K, but they claim it should have been lower, ~ 700 K, similarly to what we thought for in section 3.2; we had to stuck to the 1000 K temperature because it was a physical limit of the DRIFT-PHOENIX models. They have however selected the least energetic planetary model from Szulágyi 2017, whose models have temperatures ranging from 2000 to 10000 K. They state that in all their simulations the water snowline was located outside of the boundary of the CPD. Hence, the lowest possible value will be considered. Their lowest temperature simulation was based on a Jupiter which reached the 2000 K by the age of 1-2 Myr. This is also the case used by Cilibrasi et al. 2018. Our previous reference models, Fortney et al. 2008, were based on planets about 10 Myr old. Here we will now consider an object 5-10 times younger.
ProDiMo, in addition to the T_{eff}, also requires the luminosity of the young Jupiter. Previously, in chapter 3, the luminosity indicated by Burrows et al. 1997 has been used. The results turned out in a very cold CPD, with a snowline located at about 3 R_J. A more recent work by Mordasini, Marleau, and Mollière 2017 has shown that the previous paper may have been underestimated the young Jupiter luminosity. They have also distinguished between a hot and cold start accretion mechanism. The figure 4.9 illustrates the behaviour of the planet's luminosity considering different masses. The interest of this project is certainly focused on the 1 M_J model. At 1 Myr, the averaged luminosity is at about $5 \cdot 10^{-4}$ $L_{\odot}$. At 3 Myr it has already dropped by a factor of 10. The core accretion model presents a similar evolution. However, at the youngest age, the averaged luminosity is slightly higher, up to $8 \cdot 10^{-4}$ $L_{\odot}$, as seen in figure 4.10. The difference in the luminosity and temperature among the models defined here and in section 3.2 is due to the accretion of the planet. During this process the young gas giants keeps attracting various planetesimals and bodies of different sizes. As a consequence, these objects are going to impact onto the giant. Due to energy's conservation, the kinetic and potential energies of these impacting bodies are transformed into thermal energy, which is then gradually released by the planet. The same process also happened in other planets, like on our own Earth, which is still cooling down. Jupiter itself emits today about 1.6 times the total radiation that it receives from the Sun - this indicates the presence of an internal heat source, which would very well couple with the accretion heating trapped during its formation. It is also thought that Jupiter is still very slowly contracting (Wolf 2007).

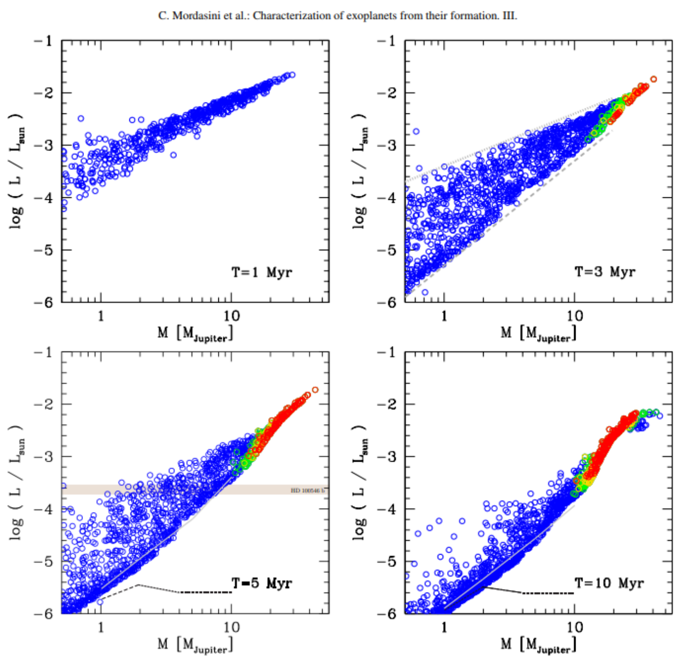

Figure 4.9: Luminosities of planets at different masses, shown at four distinct ages and considering the gravitational instability model. The various dots are the results of the various simulations. Red, yellow, and green dots correspond to planets with different fractional contribution of the deuterium burning luminosity, which involves planets more massive than our Jupiter (Mordasini, Marleau, and Mollière 2017).

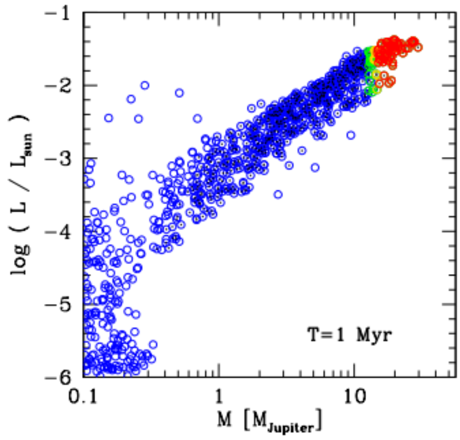

Figure 4.10: Luminosities of planets at different masses, shown at 1 Myr and considering the core accretion model. The slightly higher luminosity can be well noticed for the 1 M_J model (Mordasini, Marleau, and Mollière 2017).

On the other side, Marley et al. 2007 hypothesized a different path. This is illustrated and described in picture 4.11. They imagined a extremely high peak in luminosity at the accretion shock[1] (point 4). However the interval in which the luminosity stay above a certain threshold which would allow the snowline to be at Europa is too short in time to cope with the theoretized duration of the moons' formation.

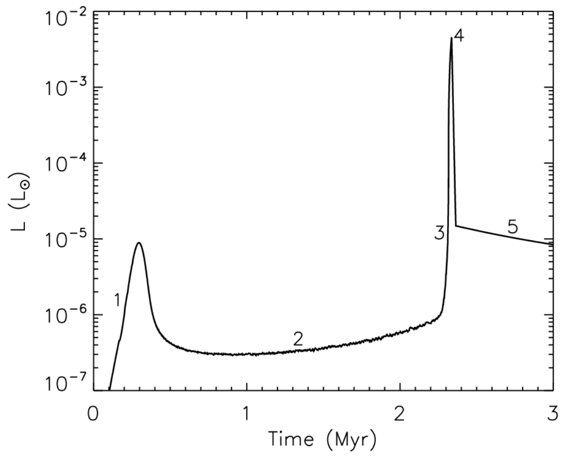

Figure 4.11: Evolutionary model of a young Jupiter. The numbers on the plot indicates: 1) Dust particles in the solar nebula form planetesimals that accrete into a solid core surrounded by a very low-mass gaseous envelope 2) The protoplanet continues to grow as the gas accretion rate steadily increases 3) Runaway gas accretion occurs and the protoplanet grows rapidly 4) During this time of rapid gas accretion, rapid increase in luminosity happens and the planet briefly shines quite brightly 5) Once accretion stops, the planet enters the isolation stage (Marley et al. 2007).

Something in between Marley et al. 2007 and Mordasini, Marleau, and Mollière 2017 will be proposed for the next attempts. It has been decided to use the following new settings, considering higher temperature and luminosity, therefore roughly estimating the formation to be happened when the planet was about 1 Myr old. The new parameters can be seen in table 4.7.

Table 4.7: The parameters which have been changed in order to consider a warmer and brighter Jupiter.

Parameter	Model F1	Models WBJ-1/WBJ-2	Unit
Luminosity of the planet	10^{-5}	$10^{-3}/5 \cdot 10^{-4}$	$[L_\odot]$
T_{eff}	1000	2000	[K]

[1]The accretion shock is the short period of time in which the accreting gas loses most of its internal entropy.

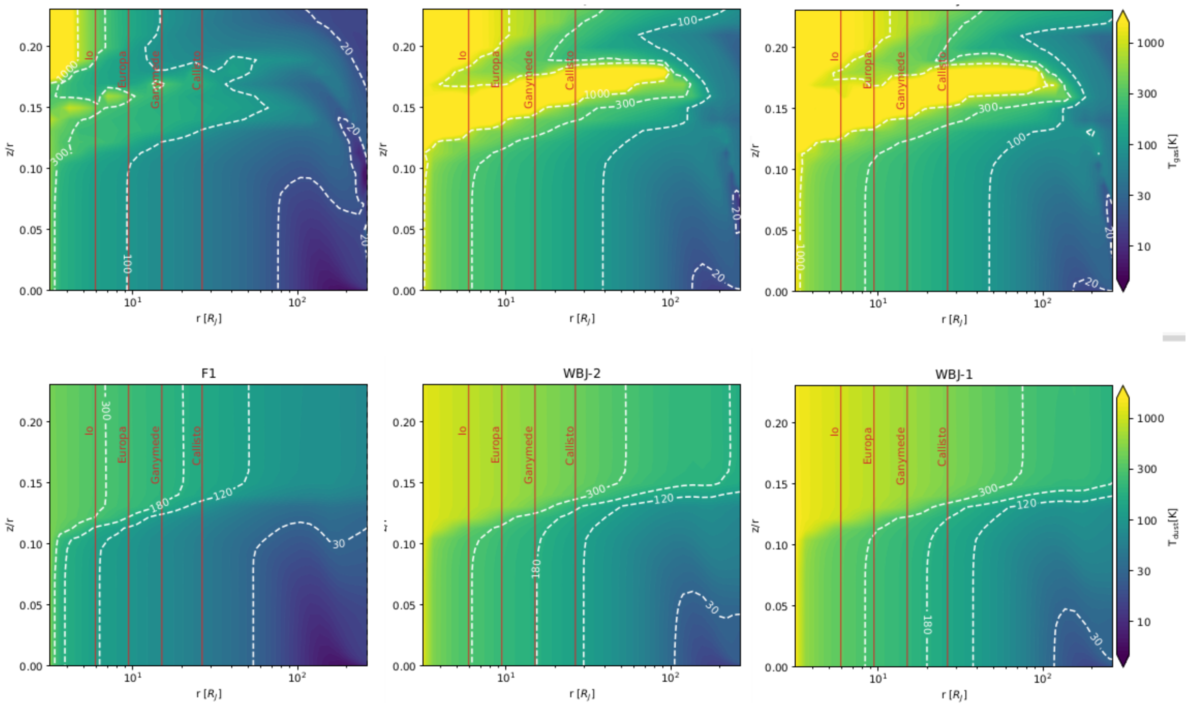

Figure 4.12: Comparisons of the dust and gas temperatures for the fiducial model F1 at 1000 K and the two new models at 2000 K, with an increasing luminosity of (model WBJ-2) $5 \cdot 10^{-4}$ and (model WBJ-1) 10^{-3} $L_{\odot}$.

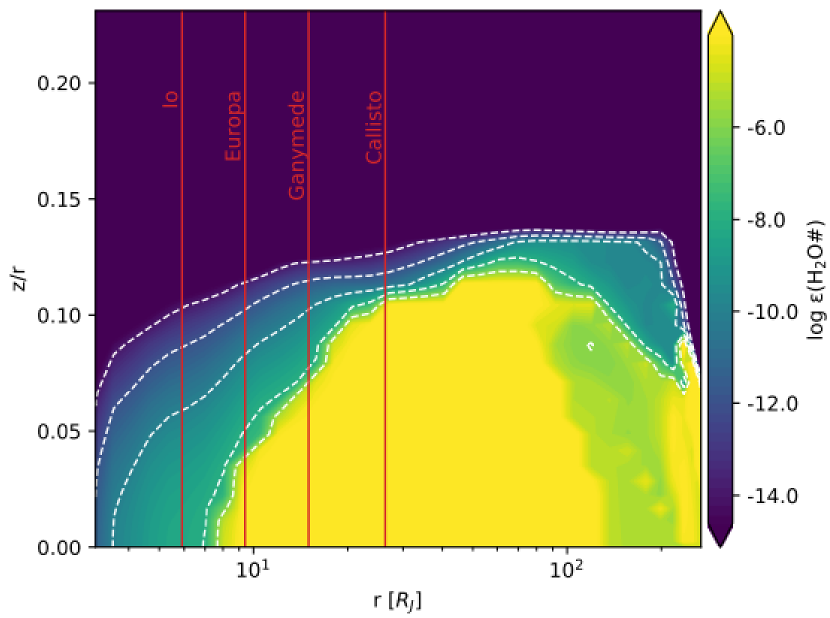

Figure 4.13: Contour plot of the water ice abundance using a T_{eff}= 2000 K and L = 10^{-3} $L_{\odot}$ young Jupiter (model WBJ1-1).

Figure 4.13 shows the abundance of the water ice within the CPD. It can be appreciated how the snowline is located around 10 R_J, almost in proximity of the Europa's current orbit. This would imply, if the satellites formed at the location they presently occupy, that the furthest moons, Ganymede and Callisto, would be full in water ice while Io's current orbit is situated in a very dry environment. Europa, which contains a 10% of water ice, is located in the proximity of the snowline. This is consistent with the current theories.

4.8. Conclusions after chapter 4

During this chapter, many simulations in which various effects have been assessed: the viscous heating within the CPD (model VH), the young Sun (model Sun), the planetary migration (model GT), a gas starved disk (model GS) and a warmer and brighter Jupiter (models WBJ-1/2). Model F1 resulted in a frozen disk, and it happened the same in every model of this chapter, apart from models WBJ-1 and WBJ-2. Especially in WBJ-1 the water snowline has moved outwards until the current orbit of Europa. This simulation agrees with the current theories, for example Miguel and Ida 2016 or Ronnet, Mousis, and Vernazza 2017. To prove that this stronger Jupiter is needed, two simulations including all the effects listed in this chapter, apart the planet which has been kept to the values of model F1, have been carried out. One for a minimum mass and one for a gas starved disk. The CPD is still full of water ice, as it happened in model F1. Hence, in order to have a snowline placed at Europa's orbit, in agreement with the current theories, we certainly need the warmer and brighter Jupiter. Figure 4.14 shows the abundances.

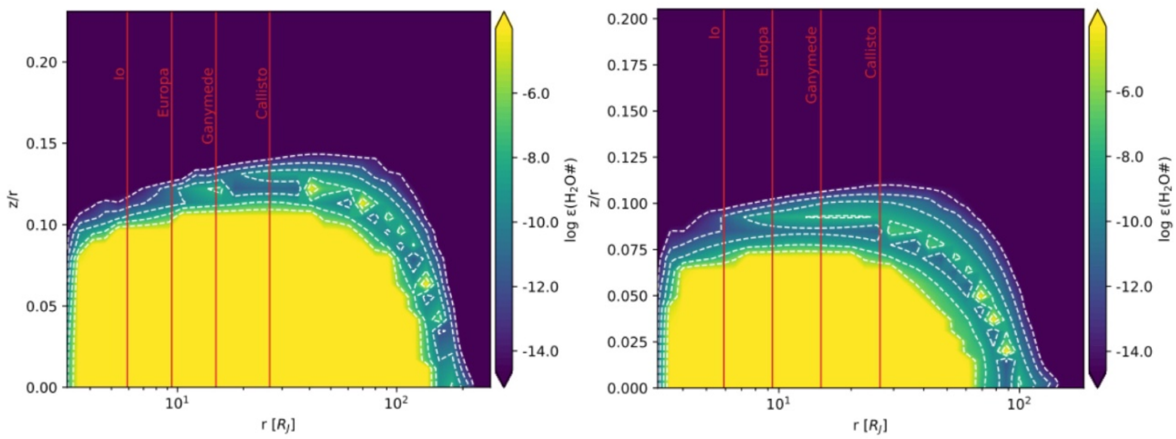

Figure 4.14: The water ice abundances of the two simulations including every feature from chapter 4 minus the warmer and brighter Jupiter, which is still the same as of model F1. On the left, a minimum mass disk and, on the right, a gas starved disk.

5

Disk with warm Jupiter: effect of different parameters on the snowline position

After the assessment of the effects on the CPD due to the various parameters defined in section 3.5 and analyzed in chapter 4 a new fiducial model has emerged, model F2, showing results in agreement with theories where the snowline is located around Europa. Its parameters are the mostly accepted in recent theories. In this chapter model F2 is further characterized, analyzing the effect of some parameters (viscous heating, the Sun, the CPD mass), in order to provide more possible realistic models for the CPD.

5.1. Second fiducial model (model F2)

From the round of simulations described in chapter 4 it appeared clear that there major source of energy in the CPD is the young Jupiter. Hence, the properties of the planet have been changed, in order to push the water ice snowline further. The new key parameters are described in table 5.1. Other parameters, which have been used to make the CPD more realistic, are also present: the CHI_ISM, to take into account the Sun, and Mdot, to consider the viscous heating. All together these changes form the second fiducial model, indicated as F2.

Table 5.1: Most significant parameters of the second fiducial model of the CPD. The fifth column indicates the section of the current chapter it which this parameter will be discussed. The last column indicates the names of the new models related to the changed parameters.

Parameter	Model F1	Model F2	Unit	Section	Model name
Luminosity of Jupiter	10^{-5}	10^{-3}	$[L_\odot]$	Sec. 5.6	Model LB
T_{eff}	1000	2000	[K]	Sec. 5.5	Model HJ
X-ray Luminosity	Not used	10^{24}	[erg/s]	-	-
CHI_ISM	1	$8 \cdot 10^5$	[-]	Sec. 5.7	Model noCHI
Dust to gas ratio	0.01	0.01	[-]	Sec. 5.2	Model DTG
Background Temperature	2.7	2.7	[K]	-	-
CPD mass	$2 \cdot 10^{-2}$	$2 \cdot 10^{-2}$	$[M_J]$	Sec. 5.4	Model GS2
Mdot	Not used	10^{-7}	$[M_J/\text{yr}]$	Sec. 5.4	Model GS2

In figure 5.1 the abundances of water (H_2O) and ice ($H_2O\#$) are illustrated, together with the location of the Galilean moons nowadays, indicated by the stars. Comparing it to the work of Ronnet, Mousis, and Vernazza 2017 shows that we are getting the water ice snowline in a very similar position (see figure 1.7).
Figure 5.2 shows the profile temperature. As a confirmation the water snowline, plotted in red, is very close to Europa's current location. It is interesting to notice how the temperature is way above the

expectations given by other authors. Ronnet, Mousis, and Vernazza 2017 were adopting a snowline of 180 K, as well as Miguel and Ida 2016. Mosqueira and Estrada 2003 used a grater value, 220 K, which is still about 50 K lower than F2's results. This can be explained by considering that the snowline is determined by the balance between the accretion of water molecules (depending on the water density in the gas) and the evaporation of the ice (depending on the binding energy). Hence, a higher density imply a higher temperature for the snowline.

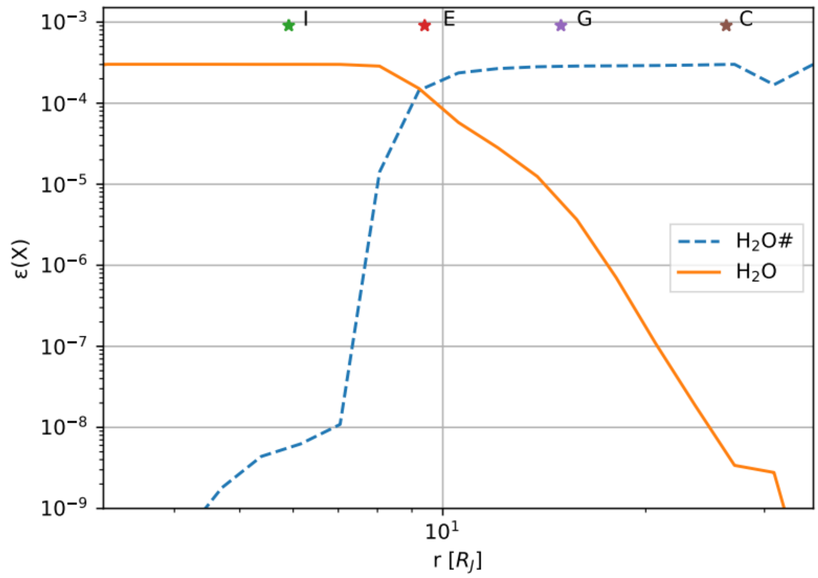

Figure 5.1: Abundances of water and ice, the latter is indicated by the # symbol. The position of the moons are indicated by the coloured stars. In the proximity of Europa the water snowline can very easily noticed, i.e. the region where the abundance of the ice is greater than the gas.

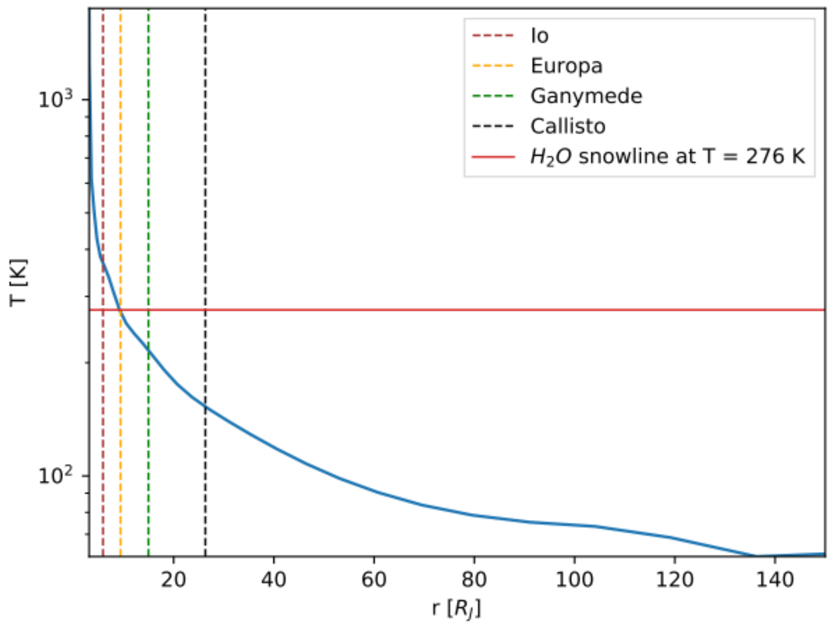

Figure 5.2: In blue, the temperature profile of model F2. In red, the position of the snowline, in this case located at T = 276 K, in the proximity of Europa. The positions of the moons are indicated by the dashed lines, as described in the legend.

5.2. Different dust to gas ratio (model DTG)

Many authors argued about having a different dust to gas ratio, mostly due to ablation of captured heliocentric planetesimals, which would have enhanced by a factor of 10 (Miguel and Ida 2016). Therefore, model F2 has been slightly modified as follows in table 5.2. The mass has been reduced in order to stick to the minimum mass model in which the dust mass is equal to the total satellites' mass ($2 \cdot 10^{-4}\ R_J$).

Table 5.2: Modified parameters for model DTG.

Parameter	**Model F2**	**Model DTG**	**Unit**
Dust to gas ratio	0.01	0.1	[-]
CPD mass	$2 \cdot 10^{-2}$	$2 \cdot 10^{-3}$	$[M_J]$

The result turned out to be quite interesting, as the snowline has moved further and occurs at a lower temperature (figure 5.3). This was expected, as the disk is now one order of magnitude less massive, and hence less dense. Therefore, the temperature needed to freeze the particles is lower.

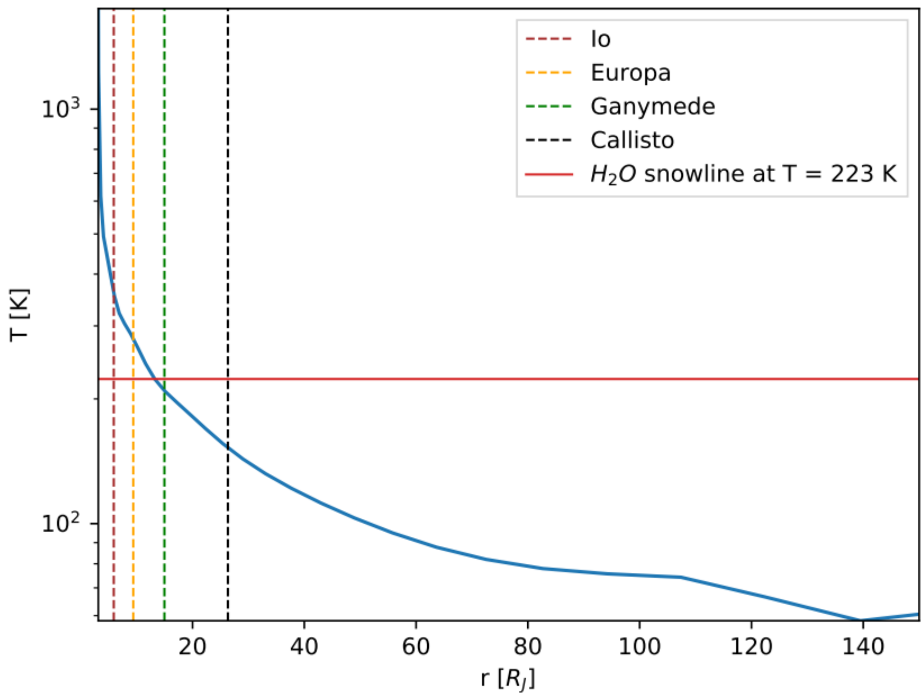

Figure 5.3: In blue, the temperature profile of model DTG. In red, the position of the snowline, in this case located at T = 223 K, in the proximity of Europa. The positions of the moons are indicated by the dashed lines, as described in the legend.

This would result in water ice present at the current locations of Ganymede and Callisto but also in a water ice free Europa's orbit, which does not agree with the present hypotheses. However, this model could be representative of an earlier phase. Lunine and Stevenson 1982 argued that the snowline had changed position, as long as the young Jupiter was cooling down. Now we are considering a luminosity of $10^{-3}\ L_{\odot}$ which is probably the peak value, according to the most recent models (Mordasini, Marleau, and Mollière 2017). It is therefore reasonable to assume model DTG as an initial state for the CPD in which the satellites started to form. A colder and less bright Jupiter would have then progressively brought closer and closer the snowline, allowing the ice to accrete on Europa only in its last phase.

5.3. Viscous heating (model VH2)

The scope of model VH2 is to show the role the viscous heating. It has been decided to look at the behaviour of model F2 assuming a greater value for Mdot, 10^{-5} M_J/yr, 100 times stronger than in model F2. This number is an average value from the peak range (10^{-4}-10^{-6} M_J/yr) proposed by Canup and Ward 2002, who was however using a gas starved and not a minimum mass CPD.

Table 5.3: Modified parameter for model VH2.

Parameter	Model F2	Model VH2	Unit
Mdot	10^{-7}	10^{-5}	$[M_J/\text{yr}]$

The midplane temperature profile of model VH2 is shown in figure 5.4. The increased viscous heating mostly affected the region after 70 R_J. The moons' location is unaffected, and the snowline has exactly the same temperature.

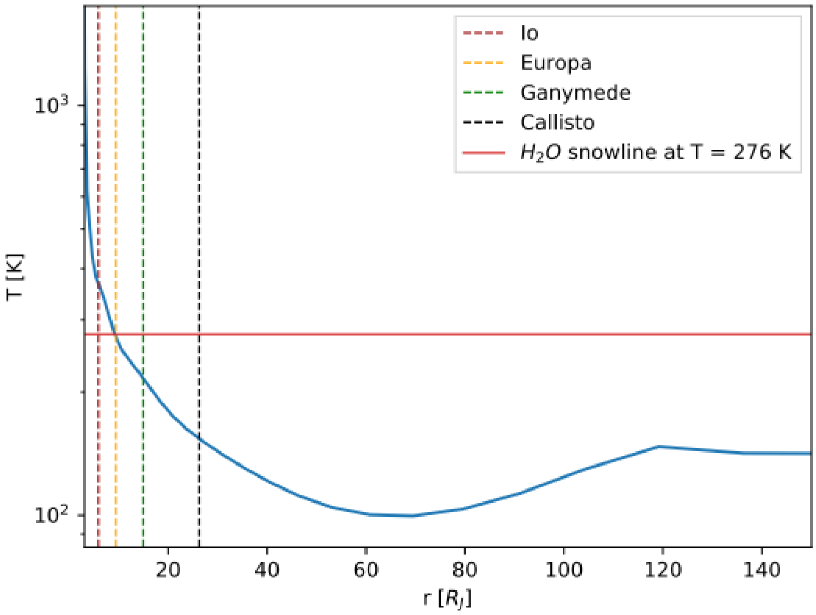

Figure 5.4: In blue, the temperature profile of model VH2. In red, the position of the snowline, in this case located at T = 276 K (the same of model F2), again in the proximity of Europa. The positions of the moons are indicated by the dashed lines, as described in the legend. The viscous heating mostly affects the external region of the CPD.

5.4. Gas starved CPD (model GS2)

Following the model GS presented in section 4.3 a new gas starved model has been selected. The CPD mass is the same than in the previous attempt, but the updated Jupiter properties, as well as the CHI_ISM and Mdot, have all been taken into account. Two different luminosities for the young Jupiter have been used, nominally $5 \cdot 10^{-4}$ and 10^{-3} $L_\odot$. In this section, only the first value is shown[1]. That is because adopting the same luminosity of model F2 would have resulted in a way warmer CPD, with the water snowline located even further than Ganymede. Model GS2 is summarized in table 5.4.
As expected, due to the lower luminosity of the planet, the temperature profile is much lower, as testified by the comparison in figure 5.5. However, a very interesting result also emerged. Even considering the less bright Jupiter as in model LB (section 5.6), in model GS2, the combined action of the fainter Jupiter and the viscous heating (enhanced by the reduced mass) is enough to produce a snowline at Europa's orbit, in accordance with the present theories. The temperature for the snowline is also more consistent to the other papers in which the authors considered the viscous heating as an important effect, such as Ronnet, Mousis, and Vernazza 2017 or Miguel and Ida 2016. This is shown in figure 5.6.

[1]The other can be found in the Appendix

Table 5.4: Changed parameters adopted in model GS2.

Parameter	Model F2	Model GS2	Unit
Luminosity of Jupiter	10^{-3}	$5 \cdot 10^{-4}$	$[L_\odot]$
CPD mass	$2 \cdot 10^{-2}$	$4 \cdot 10^{-5}$	$[M_J]$

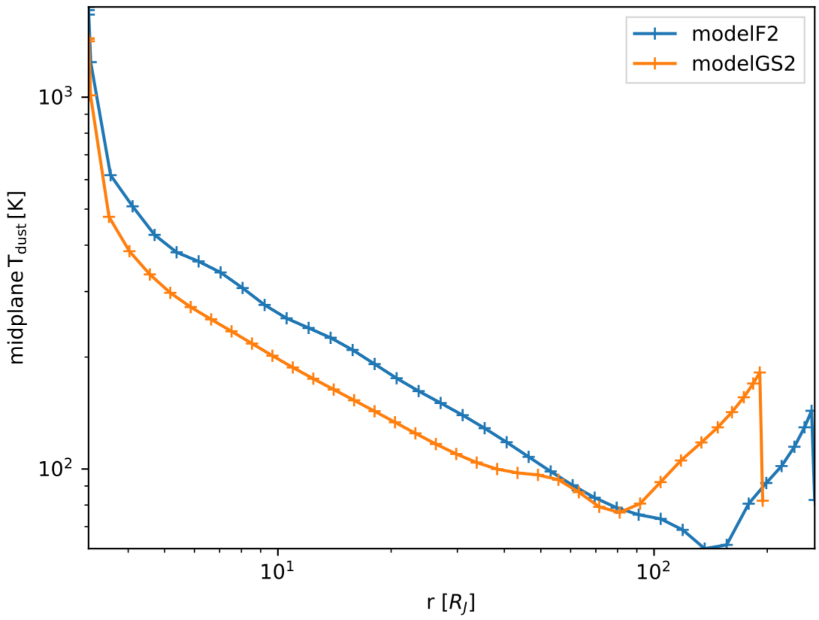

Figure 5.5: Comparison of the dust midplane temperature between model F2 and GS2. The gas starved CPD has a lower value, of about one order of magnitude, until ~ 55 R_J. Afterwards, the dust becomes really scarce and the gas starts to dominate, whose temperature increases way more, especially under the influence of CHI_ISM. The same effect can be noted for model F2, happening almost 100 $R_J$later.

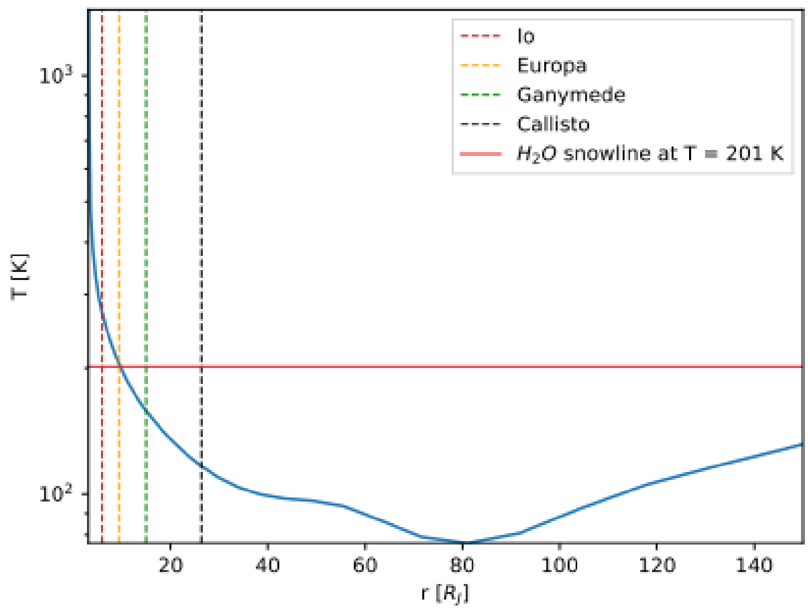

Figure 5.6: In blue, the temperature profile of model GS2. In red, the position of the snowline, in this case located at T = 201 K again in the proximity of Europa. The positions of the moons are indicated by the dashed lines, as described in the legend.

5.5. Extremely hot Jupiter (model HJ)

Szulágyi 2017 has studied the effect on the CPD of young gas giants having a T_{eff} up to 10000 K, due to the accretion heating. This was however by other authors, in primis by Cilibrasi et al. 2018. They argued that Jupiter effective temperature had to be below 1000 K in order to have ice on Ganymede and Callisto; otherwise, the entire lunar system should have been dry. However, in section 4.7, it emerged that Jupiter had to be warmer and brighter to deliver enough energy to move the snowline between Europe and Ganymede. For the sake of completeness, it has been attempted to simulate the effect of an extremely hot Jupiter, with an effective temperature of 5000 K, as summed up in table 5.5.

Table 5.5: Change in T_{eff} adopted in model HJ.

Parameter	Model F2	Model HJ	Unit
T_{eff}	2000	5000	[K]

As can be seen in picture 5.7, even a drastic change in the effective temperature of the young Jupiter hardly affects the CPD. We conclude that the dominating source of energy for the CPD is the luminosity of the planet.

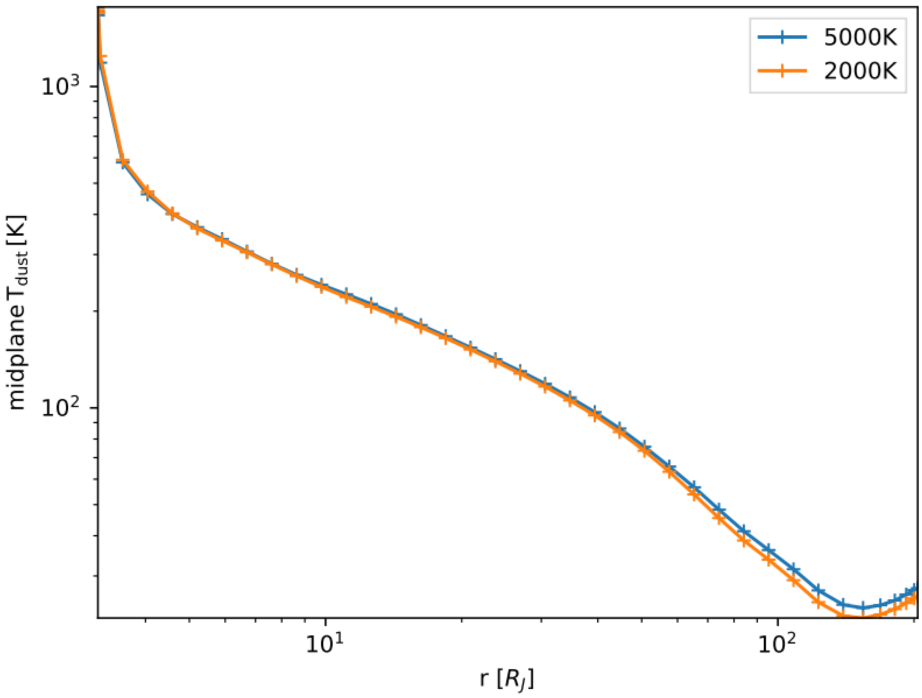

Figure 5.7: Comparison of the dust midplane temperature considering Jupiter at the T_{eff} of 2000 and 5000 K. The difference is minimal and localized in the outer disk.

Since the luminosity appears to be the driving requirement, it has also been tried to simulate a colder Jupiter, with a T_{eff}= 1000 K, but still keeping the higher luminosity of 10^{-3} $L_{\odot}$, required to move the snowline. However, in order to satisfy these two conditions, together with the mass equal to 1 M_J, ProDiMo has come up with a radius of the planet greater than a solar radius, which translates into more than 11 R_J, above the orbit of Europa.
With T_{eff}= 2000 K, the radius is about 2 R_J, which is fine for our simulations, as the orbit of the closest moon, Io, is about 6 R_J. It is also expected by the evolutionary models of Jupiter that its radius was once greater than it is today (Burrows et al. 1997).

5.6. Less bright Jupiter (model LB)

To prove how the luminosity of 10^{-3} $L_\odot$ is a key requirement a simulation very similar to model F2 has been run, with a tiny modification - the luminosity of Jupiter is assumed to be the half, hence $5 \cdot 10^{-4}$ $L_\odot$. This is also indicated in table 5.6.

Table 5.6: Change in the luminosity adopted in model LB.

Parameter	Model F2	Model LB	Unit
Luminosity of Jupiter	10^{-3}	$5 \cdot 10^{-4}$	$[L_\odot]$

Figure 5.9 compares the midplane temperatures of model F2 and LB.
The snowline temperature for model LB is not so different from model F2. Previously it was at 276 K while it is now located at 282 K. But, looking at figure 5.8, it emerges that the snowline has shifted inwards, being now almost at Io's location. This would mean that the moons should have formed closer to the planet, especially Europa, which according to model LB would have been as icy as Ganymede and Callisto.

Figure 5.8: Abundances of water and ice, the latter is indicated by the # symbol. The position of the moons are indicated by the coloured stars. The water snowline is located in the proximity of Io.

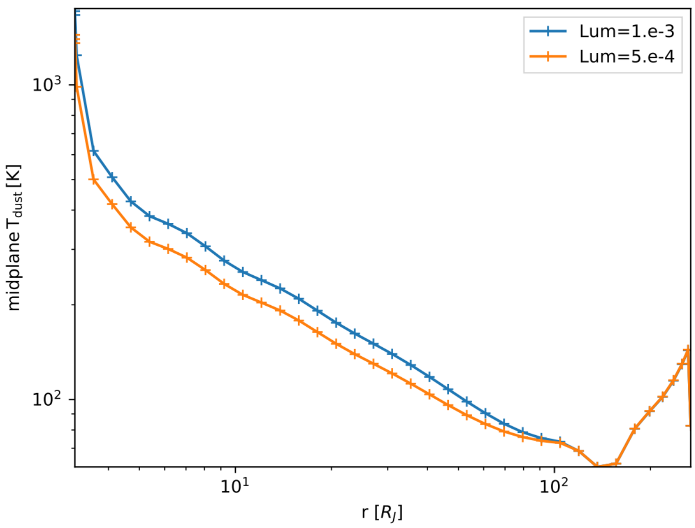

Figure 5.9: Comparison of the dust midplane temperature considering Jupiter with a luminosity of 10^{-3} and $5 \cdot 10^{-4}$ $L_\odot$. The difference ranges from 0 K, in the outer disk, to 100 K, the the moons' region.

5.7. Effect of the radiation field from the Sun (model noCHI)

The CHI_ISM parameter, adopted in section 4.5 to take into account the presence of the young Sun, is an approximation. Another option was the background heating but, as assessed in the previous chapter, the effect obtained (at least in the region of the moons, the most interesting zone for our research) looked very similar. That makes sense as the background temperature of 123 K (Cilibrasi et al. 2018) is by far due to the Sun - model BH and model CHI are both expected to take the Sun into account. Nevertheless, it is interesting to note how deeply the Sun affects the snowline - its presence increase its temperature of 70 K , as can be noted comparing the values in figures 5.10 and 5.2.
Figure 5.10 shows the temperature profile of model noCHI, which is essentially the same of model F2, minus the effect of the CHI_ISM parameter, as shown in table 5.7.
It is interesting to see the deep change in the snowline temperature, which is now at 206 K, exactly 70 K lower than in model F2. This temperature is more in line with the previously thought values: Ronnet, Mousis, and Vernazza 2017 used 180 K and Mosqueira and Estrada 2003 220 K. Also, the snowline has

Table 5.7: Change in CHI_ISM adopted in model noCHI.

Parameter	Model F2	Model noCHI	Unit
CHI_ISM	$8 \cdot 10^5$	1	[-]

shifted outwards, almost in the proximity of Ganymede's orbit. This suggests that a less bright Jupiter could create a snowline at $\sim$ 10 R_J, Europa's location. However, this option has not been investigated further since we believe that the young Sun which did have an impact on the CPD.

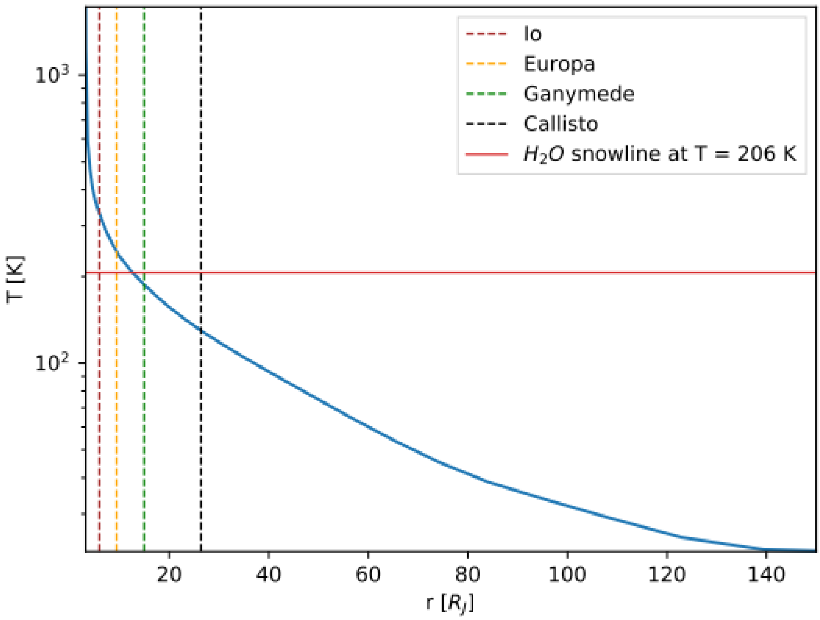

Figure 5.10: In blue, the temperature profile of model noCHI. In red, the position of the snowline, in this case located at T = 207 K, again in the proximity of Europa. The positions of the moons are indicated by the dashed lines, as described in the legend.

6
The most probable scenarios analyzed

In this chapter what we think are the probable scenarios will be presented and discussed. The expected ice abundances of those selected simulations will also be shown. In this chapter we will bring up observables which could be compared to real data, either already available or to be still obtained; for example, those which will be acquired by JUICE in the coming future.

6.1. The chosen scenarios

The list below indicates what models have been chosen, together with a brief text explaining the reason for its choice.

- Model F1: this was the first carried out model, where only the effect of the young Jupiter, at the temperature and luminosity given by Burrows et al. 1997, was considered. It turned out to be very cold. It is of interest to see the ice abundances on the satellites, considering such a model.
- Model F2: this is among the most interesting candidates emerged so far. The snowline is placed exactly around Europa's orbit which results in a less icy moons than Ganymede and Callisto, while those two outer moons both contain plenty of ices.
- Model GS2: the gas starved model is gaining more and more consensus. First sparkled by Canup and Ward 2002, it has now gathered support and has been developed and simulated by other authors as well. With our configuration we are actually able to produce the snowline at Europa's current location. Due to the gaining consensus of the gas starved theory, we consider important to describe its outcomes.
- Model DTG: some authors (Miguel and Ida 2016) have also postulated a CPD poorer in gas than the supposed PPD. Therefore, a minimum mass CPD with a dust to gas ratio enhanced to 0.1 has been simulated. This resulted in a warmer CPD, having the snowline located almost at Ganymede.

The plots in figures 6.1 and 6.2 illustrate some interesting differences among the models; respectively the temperature profile and the water abundance in the midplane. In particular, it can be appreciated how model DTG and F2 almost share the same dust temperature profile, while the snowline in model DTG is located about 4 R_J further. This can be explained by the fact that they have the same amount of dust, and the less gas contained in model DTG reduces the opacity of the disk, thus shifting away the snowline.
A similar reasoning can be made for model F2 and GS2. The second has a fainter Jupiter, which results in a lower temperature profile which pulls the snowline towards the planet. However, due to the smaller amount of mass contained in the disk, its opacity also diminishes and therefore the snowline is again pushed away. Their effects are almost balanced out, as the snowlines of GS2 and F2 are almost in the same location.

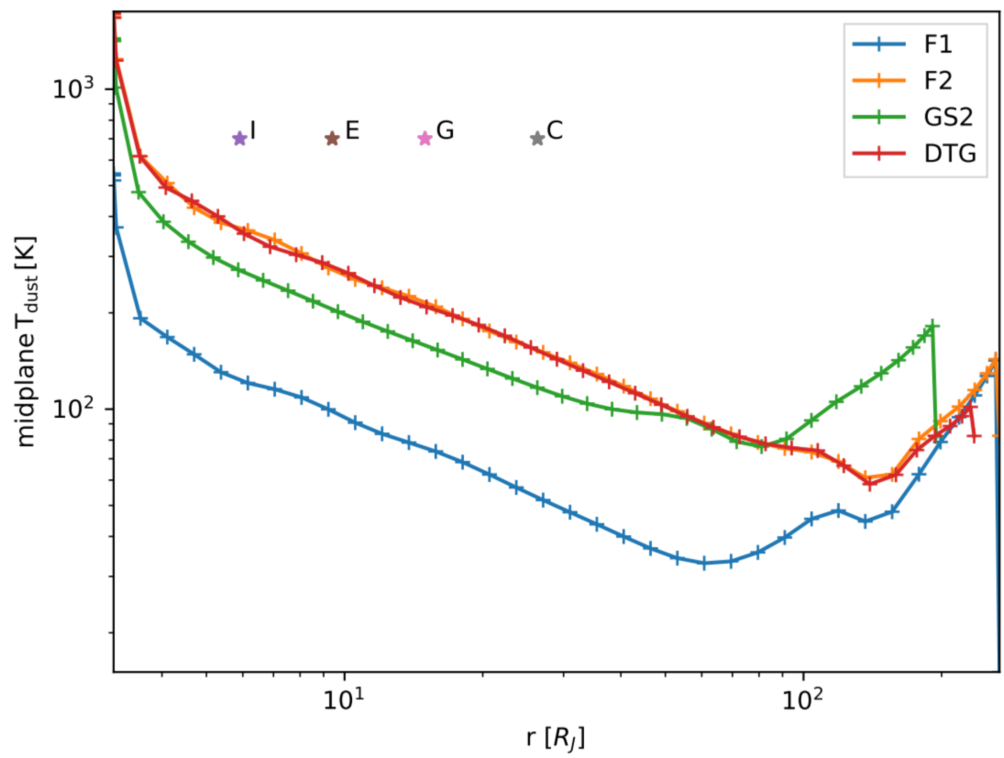

Figure 6.1: Plot indicating the different dust temperature profiles in the midplane of the aforementioned models F1, F2, GS2 and DTG. The stars indicate the positions of the Galilean satellites.

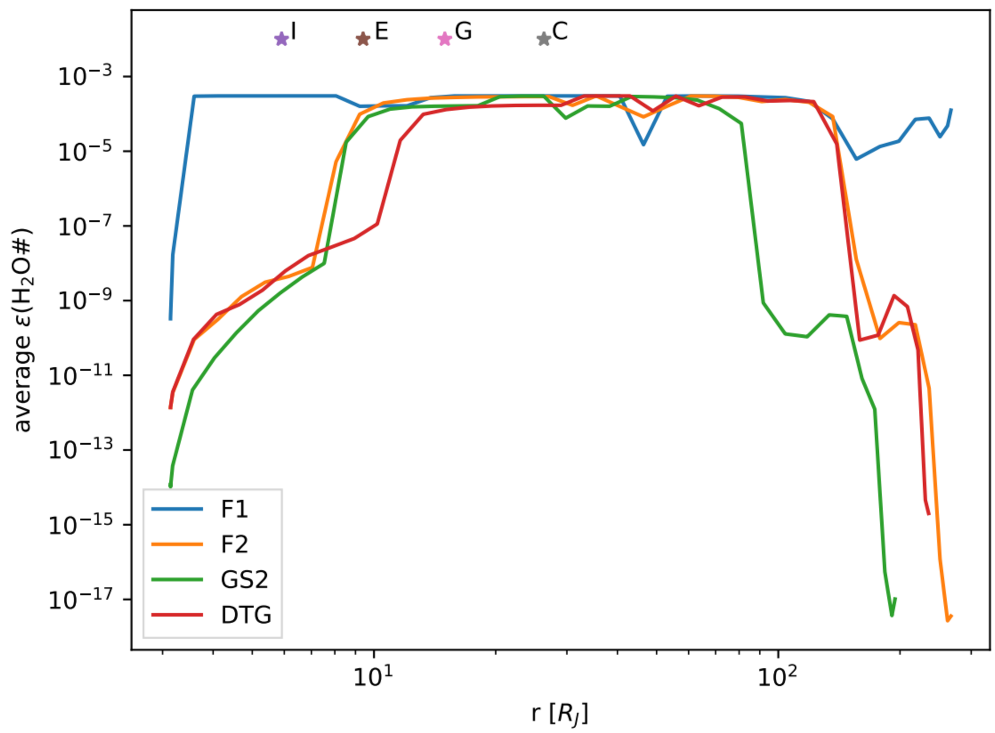

Figure 6.2: Plot indicating the different water ice abundances in the midplane of models F1, F2, GS2 and DTG. The stars indicate the positions of the Galilean satellites.

The rest of the chapter will be dedicated to a general analysis of each model, followed by comparisons with actual observational data of the moons.

6.1.1. Analysis of model F1

The model with the cold Jupiter, having T_{eff} = 1000 K and luminosity = 10^{-5} $L_{\odot}$, turned out to be full of ice, as shown in figure 3.9.
Figure 6.3 illustrates the expected composition of the ices at the current location of the four Galilean moons. In all the moons the majority would be of water ice, followed by ammonia. All the rest would consist of less than 1% of the total ice. Hydrocarbon chains appear in every moons, and a remarkable 5& of the ice at Europa's current orbit is made of CO_2.

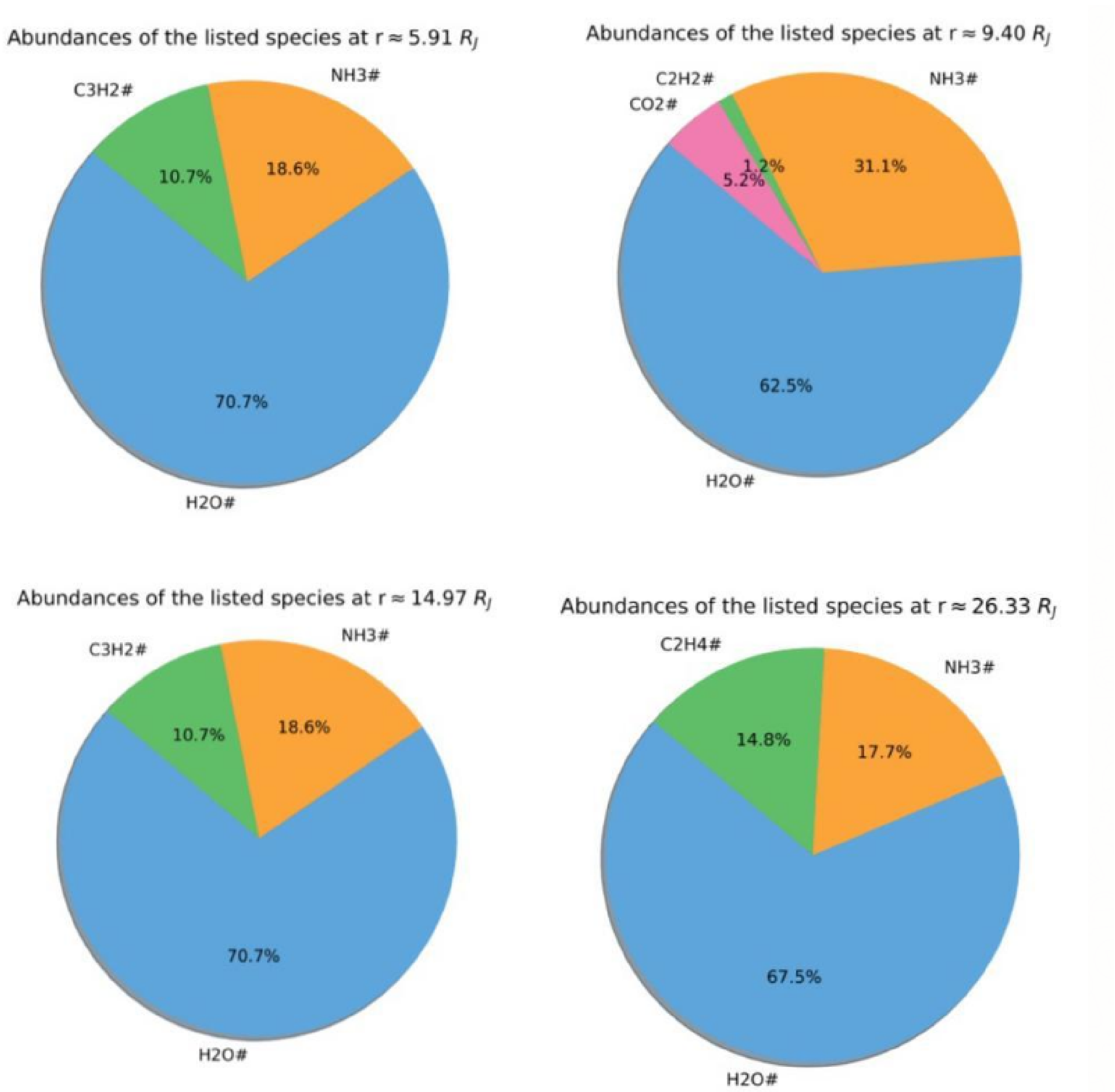

Figure 6.3: Pie charts of model F1 indicating the expected ice abundances on the present location of the Galilean moons. Top left Io, bottom left Europa, top right Ganymede and bottom right Callisto.

6.1.2. Analysis of model F2

Model F2 has been the first model displaying the snowline almost at Europa's current location, as shown in figure 5.1. It is theoretically a complete model as it that considers many processes that should have been present in the CPD such as the effect of the Sun, the viscous heating acting on the disk, a Jupiter more or less compatible with the models of Marley et al. 2007 and a minimum mass CPD.
Below the expected ice compositions at the current location of the moons are shown in figure 6.4. The ice composition at Ganymede's position is supposed to be made by the 2.5% of frozen methanol, together with a 1.4% of C_2H_5. At the level of Callisto's orbit 15% of the ice is made of C_2H_5, a carbon a particular hydrocarbon chain whose traces are also seen at Ganymede's.

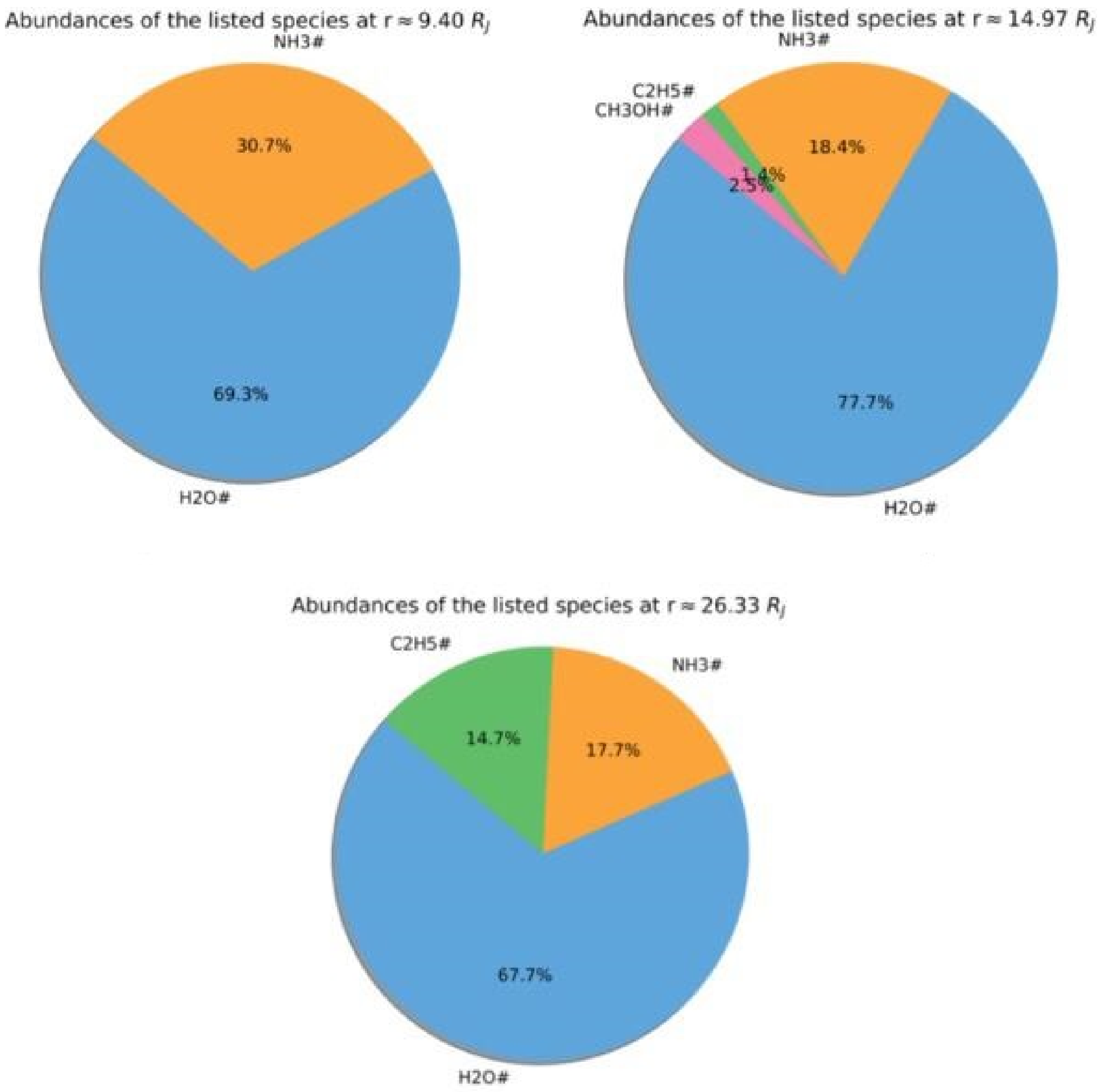

Figure 6.4: Bar charts of model F2 indicating the expected ice abundances on the present location of the Galilean moons. Top left Europa, top right Ganymede and bottom Callisto.

6.1.3. Analysis of model GS2

Model GS2 is mainly based on the hypothesis of Canup and Ward 2002. It considered a gas starved CPD, with a less luminous Jupiter ($5 \cdot 10^{-4}\ L_{\odot}$). Due to the lower mass, however, the opacity of the CPD was smaller and therefore the weaker Jupiter was still able to guarantee a snowline further than Europa, with a temperature of 201 K, 75 K lower than in model F2, as indicated in figure 5.6. It is also reasonable to think that the viscous heating affected more the CPD than it did in F2.
The bar charts contained in figure 6.5 show different ice compositions at the current location of the moons. Traces of methanolappears in Europa, while on Callisto a quite high concentration of the hydrocarbon C_2H_5 is also foreseen.

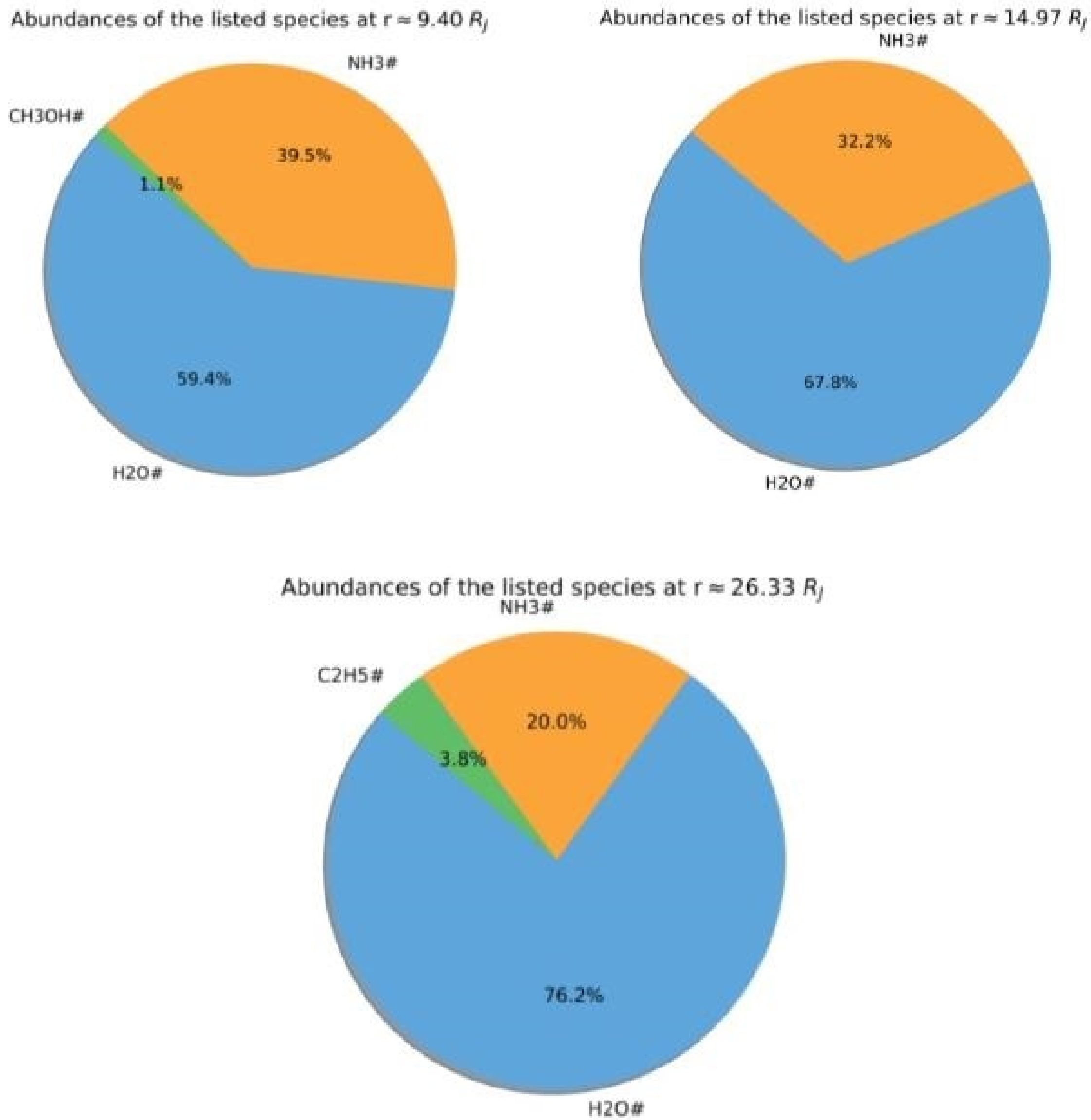

Figure 6.5: Bar charts of model GS2 indicating the expected ice abundances on the present location of the Galilean moons. Top left Europa, top right Ganymede and bottom Callisto.

6.1.4. Analysis of model DTG

In accordance with some authors, mainly Miguel and Ida 2016, a model considering a minimum mass CPD (hence possessing a solid mass of $2 \cdot 10^{-4}\ M_J$) and a dust to gas ratio of 0.1 has been simulated. Similarly to model GS2, also in model DTG the total CPD mass is below F2's mass. In both the simulations the snowline turned out to be at way lower temperatures than F2. This is probably mostly due to the different opacities of the disk. But it is also consistent to think that the viscous heating, again due to the lower mass, did play a bigger role than in F2.
The bar charts contained in figure 6.6 show different ice compositions at the current location of the moons. Traces of methanol are seen in our simulations in Ganymede, while ammonia appears to be dominant in Europa.

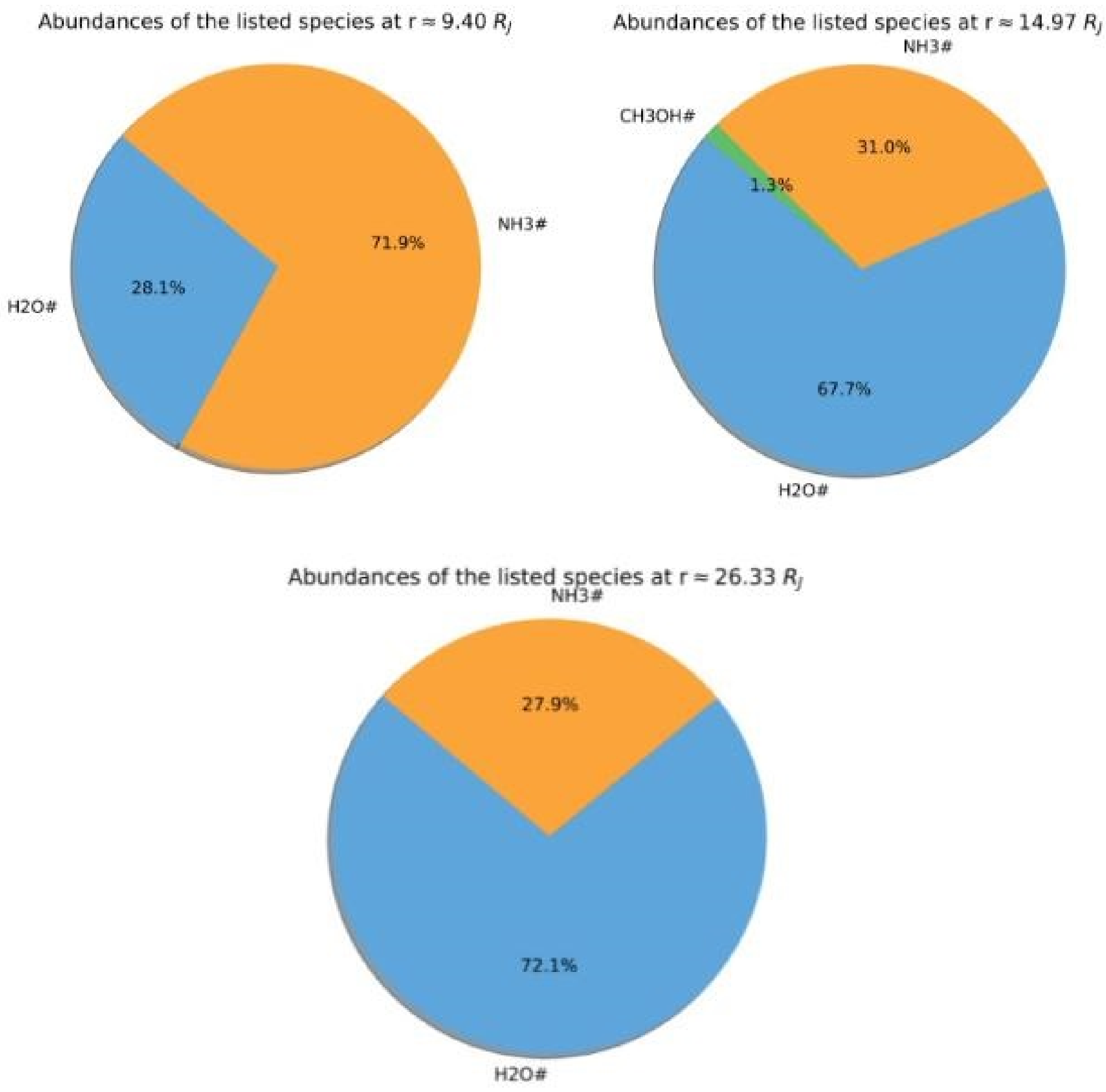

Figure 6.6: Bar charts of model DTG indicating the expected ice abundances on the present location of the Galilean moons. Top left Europa, top right Ganymede and bottom Callisto.

6.2. Ice comparison

Table 6.1 summarizes the ice species which have been so far observed on the Galilean moons.

Table 6.1: Table showing the ices which have been found on each of the three icy moons. The left column list the species while the first row indicate the names of the moons. An **x** means that the species has been observed on that moon. When present, the percentage on the total ice is also given. The right column shows the reference.

Species	**Europa**	**Ganymede**	**Callisto**	Reference
H_2O	x	x	x (90%)	Prentice 1999
SO_2		x		McCord et al. 1998
O_2		x		McCord et al. 1998
O_3		x		McCord et al. 1998
CO_2	x	x	x	Moore et al. 1999
NH_3			x (10%)	Prentice 1999

Water

The water ice, clearly, has been observed on all the icy moons: Europa, Ganymede and Callisto. In fact, the most recent theories hypothesize that the water snowline was located around Europa - which would explain the 50 % rich in ice Ganymede and Callisto, the 10 & of Europa and the dry Io. This has also been one of the leading path during this project. For every model analyzed in this chapter we are able to observe H_2O in all the three icy moons, apart from model DTG where the snowline is a bit too far away for Europa, which is dry. On the other side, in model F1 even Io turns out to be full of water ice, which is not the case for the present Io, since it is dry. It may have lost its water later, during other process. But again, in model F1.

Ammonia

Following a very similar behaviour of water ice, also frozen ammonia (NH_3) is observed in any icy moons, excluding Europa in model DTG and including Io in model F1. From the models developed with the data of the Galileo probe, it is estimated that roughly 10% of the ice on Callisto is made of ammonia while the other 90% consists of water (Prentice 1999). In general, what we found is about twice the value, apart for model DTG where it is even 2.7 more abundant. Concerning the other moons, so far the ammonia ice has never been spotted. It is also possible that simply it has not been found yet, or that it does not exist. In the latter case, it could be an issue related to the chemical network.
Traces of methanol are observed in many simulations. However, this particular compound has never been observed in the Galilean moons, but only postulated by laboratory experiments (Hudson and Moore 1999).

Sulfur dioxide, oxygen and ozone

Frozen sulfur dioxide (SO_2) and oxygen (O_2) have been spot on Ganymede (McCord et al. 1998). The following figure 6.7 shows the respective abundances. While the first molecule does appear in the frozen state (actually for all of the icy moons), we cannot say the same for the oxygen. The ozone is not present in the chemical network.
Calvin, Johnson, and Spencer 1996 and Boduch et al. 2016 suggested possible formation mechanisms for respectively O_2 and SO_2 & O_3. This could explain the absence of frozen oxygen in shown in figure 6.7.

Carbon dioxide

Carbon dioxide is present in all the icy moons (Moore et al. 1999). Considering, for example, model F2, the CO_2 abundance is shown in figure 6.8. The external shape looks like a classical output for the H_2O ice but, at in certain points the abundance drops drastically. Further analyzing those regions in figure it can be noted that most of the carbon ends up into hydrocarbon chains, in this case c_2H_5 and C_3H_2. This may be correct, or there may be again some discrepancies in the chemical network, since most of the carbon, in certain regions, lands up into those chains. This is also witnessed in the pie charts shown before, where a couple of orbits has even more than 10% made of (a combination of) hydrocarbon chains.

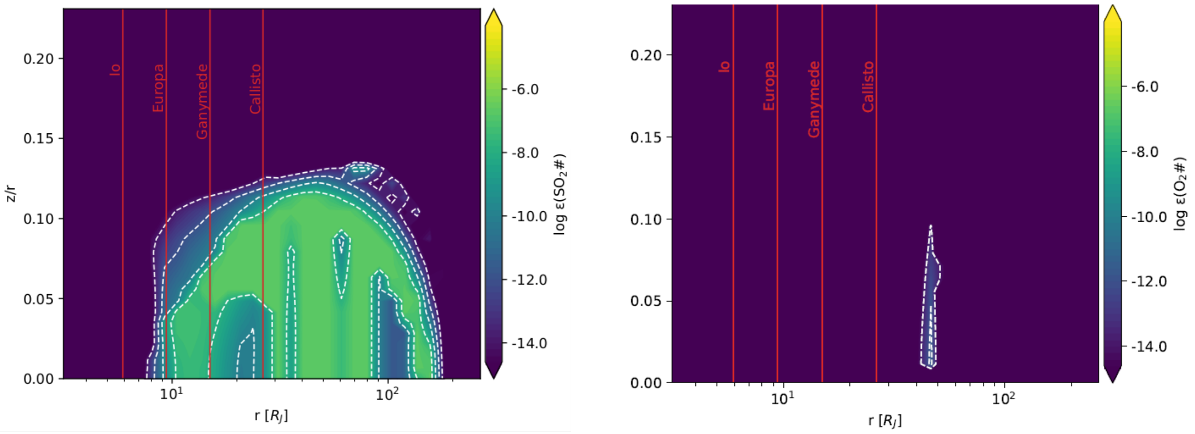

Figure 6.7: The abundances of the frozen SO_2 and O_2 in model F2.

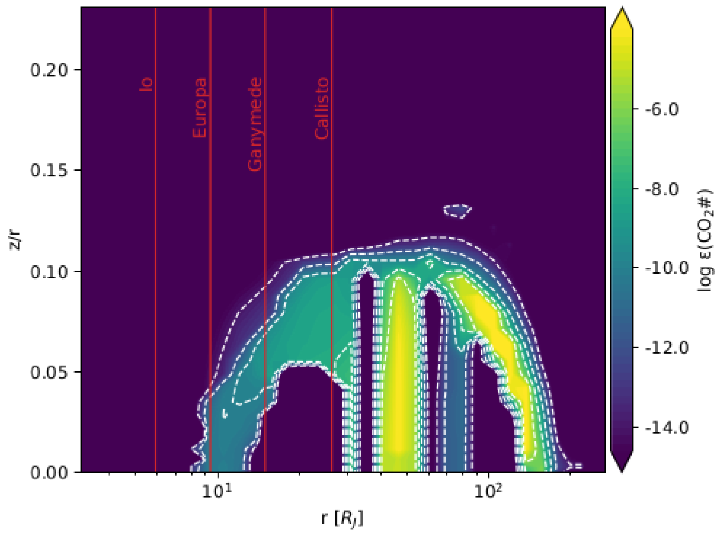

Figure 6.8: The abundances of the CO_2 ice in model F2. The unexpected behaviour can be noted.

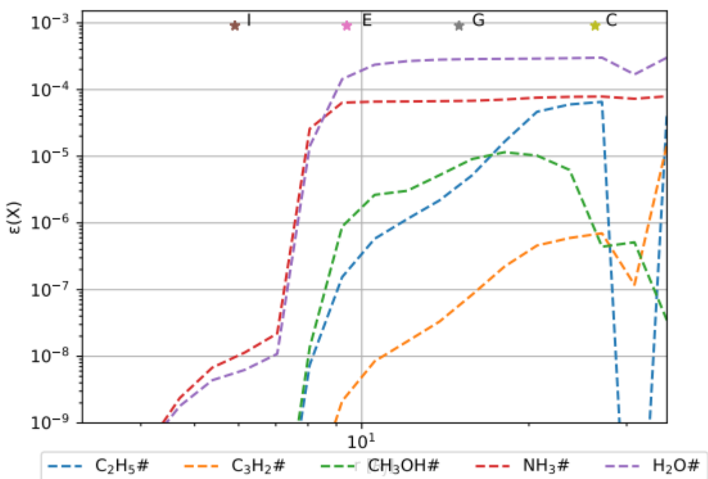

Figure 6.9: The abundances in the midplane of the listed species, shown in the y-axis. The x-axis represents the distance from the planet, expressed in Jovian radii.

The other models (GS2, DTG and F1) present similar characteristics for the all the described species, scaled to the respective temperatures. For example, model F1 foresees frozen carbon dioxide even in the proximity of Io. Model GS2, shows the CO_2 closer to the planet while, model DTG, a little bit further. The following two figures show these two different abundances, which can help to add further constraints to the CPD. They again present the same particular behaviour of model F2, having the CO_2 abruptly disappearing into hydrocarbon chains.

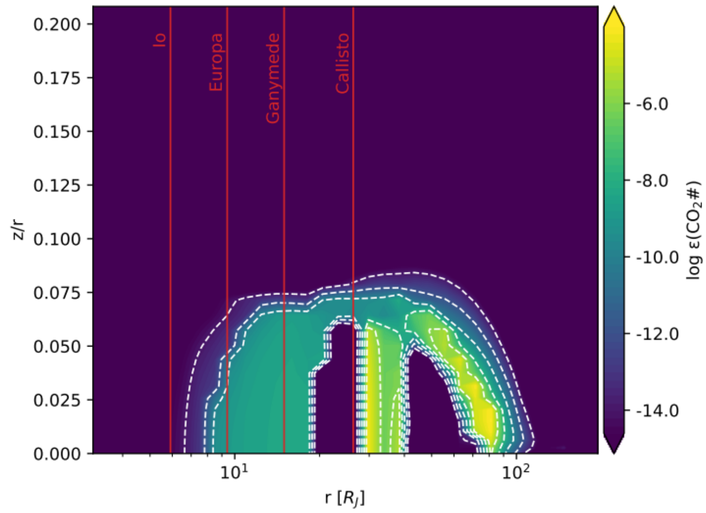

Figure 6.10: The abundances of the CO_2 ice in model GS2.

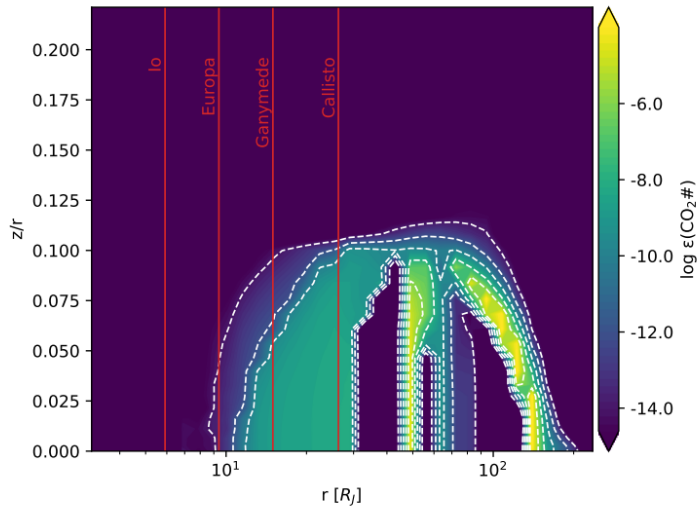

Figure 6.11: The abundances of the CO_2 ice in model DTG.

7
Conclusions

This chapter will try to summarize all the findings emerged from the thesis project. Recommendations and ideas for future works are also suggested.

7.1. Outcomes

Based on the work performed during this thesis project, the following conclusions have emerged:

- To reproduce current theories where the snowline is located around europa, the CPD should have been dominated by the young Jupiter, in particular by its luminosity. The moons must have formed while the planet was still accreting, otherwise its luminosity would have been too small to heat up the disk to have the snowline around Europa.

- The viscous heating did play a minor role in the heating budget of a minimum mass CPD. However, as the total mass of the disk decreases, it starts to be more and more important.

- The young Sun influenced mostly the upper and outer regions of the CPD, due to the intrinsic opacity of the disk. However, as shown in section 5.7, it also increased the absolute value of the snowline.

- Heller, Marleau, and Pudritz 2015 are correct in affirming that the moons cannot have formed during the GT scenario, since in model GT there is less water ice at the location where Callisto is present today. This is true for the case of the massive disk, and would be even worse with a gas starved model.

- Considering the type I migration (Canup and Ward 2002) illustrated in section 1.2.1 the moons may have formed even more externally than their actual locations. In this case, an even warmer Jupiter would be required, which cannot really be explained by the current models of young gas giants.

- The minimum mass (Mosqueira and Estrada 2003, Miguel and Ida 2016) and the gas starved (Canup and Ward 2002) models both gave results in line with the current hypotheses on the moons' formation. However, the second theory require a less powerful Jupiter, which would be more in line with the current models for the young giant. A very recent support for the gas starved disk came out very recently last November, in a paper which constrained the CPD mass to a smaller value than the minimum mass requires (Pineda et al. 2018).

- The water snowline temperature, which previously only had fixed values given for the different models, takes now a consistent value, based on the chemistry. Depending on the model, it can vary a lot, but it is generally larger (always above 200 K, with the exception of model F1) than previously thought (Miguel and Ida 2016 said 180 K, Ronnet, Mousis, and Vernazza 2017 170 K and only Mosqueira and Estrada 2003 proposed a greater value, 220 K.)

In chapter 6 the expected ice compositions of the moons, given different models, are shown. However, in order to not be dispersive, it has been decided to limit those to four models and to the actual location of the moons. ProDiMo allows to see the results in any point of the CPD and for any models. For future works, many possibilities are still open. The ice composition within the disk could be used to test the different scenarios, assuming that moons formed from the ices present at the location where their current orbits are, as has been done for CO_2 in section 6.2.
A very recent paper from Pineda et al. 2018 has calculated constraints for circumplanetary disks, from observational data of a planetary system where the young gas giant has about 1.65 M_J. The relation between the planet and the CPD mass is not straightforward, but it is realistic to assume that this slightly larger planetary mass implies a bigger mass for its related CPD, compared to our Jovian model. According to Pineda et al. 2018, the upper limit is 1.44 M_E, which translates into $4.5 \cdot 10^{-3}$ M_J. This is about 20 times smaller than the massive disk considered in models F1,F2 and DTG. But, it is above the mass considered in model GS.

7.2. Recommendations

ProDiMo is a software meant to model PPDs. After this thesis, we can say that it can also work very well in simulating a CPD. It is advised to use this powerful tool to model circumplanetary disks also around exoplanets. It can help the scientists to understand what the composition of the moons based on the boundary conditions of the disk. In particular, to foresee the existence of moons full of water, of which part could be delivered into a subsurface ocean maybe capable of hosting life, similarly to what is thought for Europa.
Some improvements which could greatly enhance the quality of the software are suggested below.

7.2.1. Viscous heating

One of the major improvement which is suggested is to modify the tool which handles the viscous heating. Currently there are two available options:

- Using the Mdot mass accretion rate, as explained in section 2.2.4. This method has been extensively used during this thesis project.
- The second method involves the more classical approach of defining the turbulent parameter α. Two simulations have been run during this project; however, the results turned out to be physically wrong, and it has then be decided to not report them in this thesis and not to further consider the turbulent parameter.

It would be very interesting to fix this tool. The Mdot based viscous heating looks to be scarcely effective. It may be correct, but it certainly needs more investigation and validation. A good alternative could indeed be the turbulent parameter α. According to Ronnet, Mousis, and Vernazza 2017 the viscous heating plays a major role, probably bigger that our findings - for future work this should be understood and corrected.

7.2.2. The effect of the Sun

Since ProDiMo has been designed to simulate protoplanetary disks, which are usually "isolated", a feature to simulate a strong source of radiation was not incorporated. Other minor components, such as the CHI_ISM and the cosmic rays were integrated. The first one turned out to be very useful to give a rough approximation of the presence of the young Sun the Jovian CPD, as also corroborated by model BH (section 4.4). However, foreseeing more and more works using ProDiMo into the fascinating topic of CPDs, it would be important to design a proper tool which could simulate a young star not too far from the disk, maybe taking into account its evolution. The background temperature and the CHI_ISM can give a good first guess, but for more precise simulations, a proper design is required.

7.2.3. The chemical network

From the analysis of section 6.2, in all the models the CO_2 ice disappears in "random" areas, which should have contained it, similarly to the H_2O ice behaviour. Looking into the abundances of every species, we notice how all the carbon disappears in those same zones to form the icy hydrocarbon chains, mostly C_2H_5. This behaviour is a bit strange, and it happened some more times in other

simulations. This means, probably, that the chemical network needs some more testing in order to be adapted to the different world of the CPDs, compared to PPDs. It could also be correct, but it is certain an element which needs a full check.
Other two major suggested improvements are more specific. First, the chemical network currently used does not include the hydrogen peroxide (H_2O_2) and ozone (O_3), which have been observed in the Galilean satellites (Carlson et al. 1999,McCord et al. 1998). It is highly recommended to include them in the network. Secondly, the grain surface chemistry is not included either. While in principle ProDiMo is coded to have it (Woitke 2013), it turned out to be not working. It is also highly suggested to correct this interesting tool.

7.2.4. Time dependent simulations

Generally speaking, the luminosity of a young gas giant drops drastically within some Myr, compared to the luminosity of a young star which is way more stable. For this reason, while for the simulation of a PPD a constant value for the luminosity of the central star is more than accurate, in the simulations of a CPD it could really make the difference. An example is the shift of the snowline, as proposed by Canup and Ward 2002, which could explain the small quantity of ice on Europa compared to Ganymede and Callisto. ProDiMo can already produce for time dependent simulations, however keeping constant the properties of the central object. Allowing the user to change it during a time dependent simulation would be highly beneficial.

Appendix

Model GS2 with a brighter Jupiter

Model GS2 turned out to be an interesting candidate. Its differences from model F2 are the mass, which changed from a minimum mass to a gas starved CPD, and the luminosity of Jupiter, which decreased from 10^{-3} to $5 \cdot 10^{-4}$ $L_{\odot}$. An attempt with the same luminosity of model F2 has also been simulated. Figure A.1 shows how the same luminosity of model F2, applied to model GS2, results in a too warm CPD, as Europa, if it would have formed at its current orbit, would have been almost ice free. However, this simulation could be showing an early stage of the CPD, before the moons' formation. The gradual cooling of Jupiter would have then later neared the snowline, in the scenario represented by model GS2.

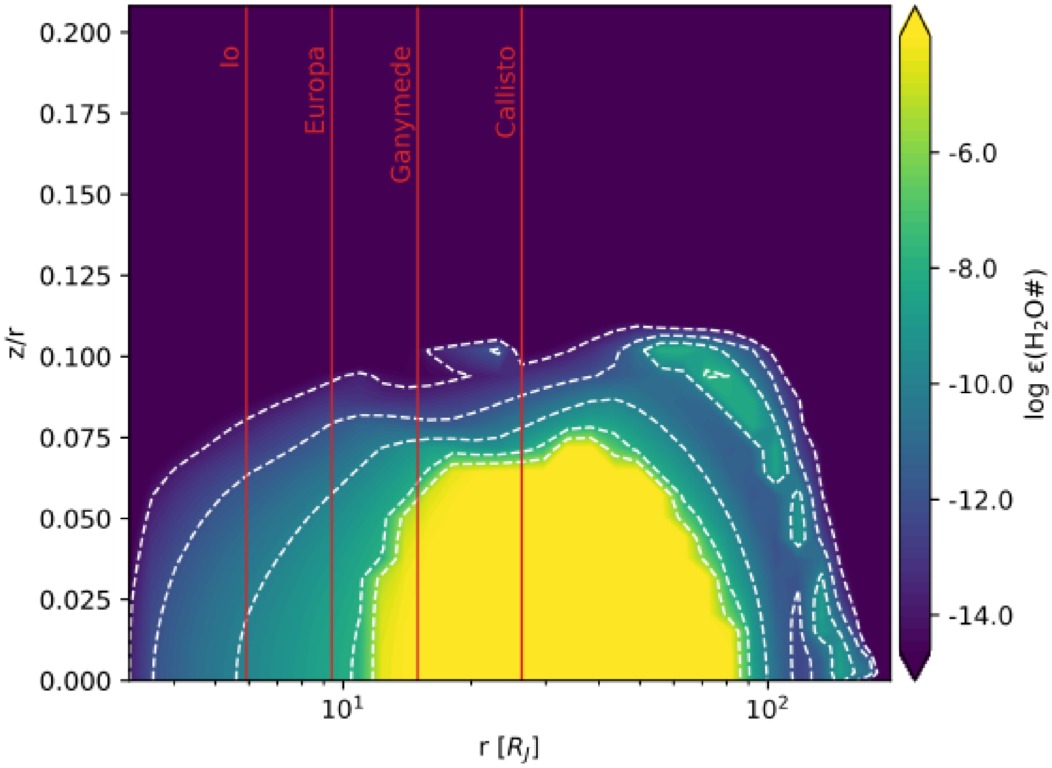

Figure A.1: The water ice abundances of the modified model GS2 including a brighter Jupiter.

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