The chemical composition of hot and cold gas giants

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Abstract

Exoplanet surveys have identified a category of giant planets that orbit very close to their host stars — the so-called hot Jupiters. The origin of such hot Jupiters is a long standing puzzle and has been closely investigated since the first discovery of such planets in 1995. The two competing formation paths suggests that they either migrated inwards during their formation process, through gravitational interactions with the disc, or that they formed further out in the disc and was scattered inwards later due to disc-free interactions. The question is, how do we separate between these two cases? One approach is to study their chemical composition. In this thesis I will study growth-tracks of hot and cold Jupiter planets that has been produced in a detailed model of an evolving protoplanetary disc, where all growth is due to the accretion of pebbles, and use these to deduce the chemical evolution of the core and gas envelope of such planets. Two sets of volume mixing ratios were used, where one is adapted from observations of gas and ice in protoplanetary environments and the other from theoretical calculations of a solar composition disc. The aim of the work is to calculate the carbon to oxygen number ratio of hot and cold Jupiter planets, where cold Jupiter planets have a semi-major axis larger than 1AU and represent the planets that might be scattered inwards due to disc-free interactions. For both sets of volume mixing ratios, I find that the gas envelope of hot Jupiters are oxygen dominated with a number ratio of around 0.7, while cold Jupiter planets has an equal amount of carbon and oxygen in their envelopes. The cores of both types of planets are heavily oxygen dominated, and when theoretically calculated volume mixing ratios are used some planetary cores even turn out to lack carbon completely. These results can be used to separate between the two formation paths of hot Jupiters. If an astronomer were to find a gas giant in a tight orbit with a C/O ratio in the envelope around unity, then it is most likely a cold Jupiter planet that migrated by interacting gravitationally with another planet or a binary star after the dissipation of the gas disc. To conclude, the carbon to oxygen number ratio in exoplanet atmospheres has shown to be useful when separating between the two formation paths of hot Jupiter planets.

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Populärvetenskaplig beskrivning

Heta Jupiter planeter är gasjättar som befinner sig i en omlöpssbana närmare än 0.1 AU från stjärnan de kretsar runt, och vars massa till största del är i gasform. Upptäckten av sådana planeter i exoplanetssystem har förundrat forskare i årtionden, eftersom moderna teorier rörande planetformation föreslår att formationen av gasjättar sker längre bort från den centrala stjärnan, utanför den så kallade snölinjen.

Denna diskrepansen kan löjas om man tar hänsyn till att planeter kan migrera genom den protoplanetariska disken som de föds i under sin tillväxt, så kallad planetmigration. I stället för att formas på plats, vilket inte hade stämmt överens med moderna teorier kring hur planeter bildas då det inte finns tillräckligt mycket tillgänglig massa så nära stjärnan, så kan planeter börja sin formation väl utanför snölinjen och sedan vandra inåt genom disken under själva formationsprocessen. Bevis för att sådana processer äger rum och information om var planeterna ursprungligen påbörjade sin formation kan härledas från planeternas kemiska sammansättning, vilket är just vad jag kommer att studera i mitt kandidatarbete.


Contents

1 Introduction .................................................. 2

2 Background theory and modeling a planetary disc .......... 6
   2.1 The protoplanetary disc model .......................... 6
   2.2 Planet migration ......................................... 9
       2.2.1 Planet-disc interactions of low mass planets – Type I migration 9
       2.2.2 Planet-disc interactions of massive gap opening planets – Type II migration ................. 12
   2.3 Pebble accretion and gas accretion .................. 13

3 Method ....................................................... 16

4 Presentation of results ....................................... 19
   4.1 Evolution of total mass .................................... 19
   4.2 Icelines .................................................. 21
   4.3 Evolution of chemical species ............................ 23
   4.4 Carbon to oxygen ratio - case 2 .......................... 25
   4.5 Carbon to oxygen ratio - case 1 ........................ 26

5 Summary .................................................... 29
Chapter 1

Introduction

Protoplanetary discs are found around young stars and are a product of star formation. When the molecular cloud that the star is formed from starts to collapse due to self-gravity, it becomes denser and the random gas motion averages out in the direction of the collapsing cloud’s net angular momentum. As the radius of the cloud decreases, conservation of angular momentum causes the gas to rotate faster, eventually causing the cloud to flatten out and take the form of a disc. This disc is the birthplace of planets.

The protoplanetary disc is predominantly composed of gas with a small fraction of dust particles, mostly micrometer-sized, embedded in it. Such small particles are strongly coupled and move with the gas. These so-called dust grains grow to mm–cm sized pebbles through the processes of collision or sublimation and condensation cycles around ice lines (Johansen et al., 2014). Collisions between particles smaller than millimetre or centimetre sizes are very likely to lead to adhesion, while collisions between larger particles in general lead to fragmentation. In sublimation and condensation cycles, the layer of ice on particles that are drifting across the snow line sublimates and drift back outwards where it condensates on other particles. Over time, most particles drift across the snow line towards the central star, leaving only a small amount of particles behind that can grow effectively.

When the particles reach pebble sizes, they gradually decouple from the gas and begin to drift inwards towards the central star (Whipple, 1972; Weidenschilling, 1977a). If these swarms of drifting pebbles reach a concentration high enough for gravity to overcome the tidal pull from the star, they collapse to form planetesimals due to self gravity. Such high concentrations can be present due to several mechanisms. One of these mechanisms is the so-called streaming instability where solids and gas in the disc interact via aerodynamic drag which ultimately leads to particle concentration high enough to seed planet formation (Youdin & Goodman, 2005). Particles can also concentrate in vortices (Barge & Sommeria, 1995) and in pressure bumps (Whipple, 1972). These planetesimals that form from gravitational collapse of pebble swarms have sizes on the order of 100 – 1000km (Lambrechts et al., 2014). The largest planetesimals could act as a seed for further growth and are then called planetary embryos.

Within the core accretion scenario, there are mainly two theories describing how the growth continues after this. The planetary embryo could keep on accreting planetesimals.
Figure 1.1: This figure is a reproduction of Fig. 1 from Lambrechts et al. (2014). It shows the accretion rate of planetesimals (grey), the accretion rate of pebbles (red) and the minimum accretion rates required to sustain a stable gas envelope (black), as a function of the core mass. The labels that belong to the latter black curves represent the H$_2$O pollution of the atmosphere with respect to pure H/He nebular gas. Accretion rate curves in the yellow dashed region does not manage to form the cores of the giant planets within the dissipation time of the gas disc. The red circles represent the end of pebble accretion — the pebble isolation mass.

However, this is a slow process and, unless the abundance of solids in the disc is increased to several times the solar value, it takes a longer time than the lifetime of the disc itself (Pollack et al., 1996; Rahikov, 2004; Levison et al., 2010). This problem can be fixed by taking into account the accretion of pebbles onto the planetary embryo as well (Johansen & Lacerda, 2010; Ormel & Klahr, 2010; Lambrechts & Johansen, 2012; Morbidelli & Nesvorny, 2012). Since the protoplanet accretes all pebbles entering its Hill sphere, pebble accretion is a very fast process, see Figure 1.1.

During pebble accretion the planetary embryo also begins to attract a gaseous envelope. However, due to pebbles falling down through the protoatmosphere, the envelope can not be contracted until the accretion of pebbles is halted. This happens when the so-called pebble isolation mass is reached (see section 2.3). After this, the gas envelope can be contracted and further gas accretion continues until the dissipation of the gas disc.

An important mechanism that has not yet been explained is the process of planetary migration. During growth the protoplanet interacts with the gas in the disc and migrates through it (Ward, 1997). There are two main migration regimes called type I, for low mass planets still embedded in the disc, and type II, for higher mass planets that have opened up a gap in the disc (Lin & Papaloizou, 1986b). Type I is faster than type II and
Figure 1.2: This figure is a reproduction of Fig. 1 from Bitsch et al. (2015b). It shows the zones of outward migration at different times for planets in type-I regime. Planets located inside the solid lines will migrate outwards.

is proportional to the mass of the planet. The effects of migration become important when the planets have reached a mass of around 1 $M_E$ and it is most severe around 10 $M_E$. After reaching pebble isolation mass and when the planet has accreted a certain amount of gas it starts to open up a gap in the disc. Such a planet adjust its position so that it sits in the center of the gap. At this phase migration in the type II regime sets in and the migration timescale will be the same as the accretion time scale of the disc (Baruteau et al., 2014).

One interesting thing about migration is that it does not have to be directed inward. Strong negative radial gradients in several parameters can result in outward migration in certain regions of the disc (Paardekooper & Mellema, 2006b; Kley & Crida, 2008; Baruteau & Masset, 2008; Kley et al., 2009). These regions are found in the inner part of the disc and at early times they are quite wide and host planets of a wide range of masses. As the disc is accreted by the star, the regions of outward migration will shrink and only have the capability to host low mass planets, see Figure 1.2.

If one would like to learn something about how a planet has evolved, one could study its chemical composition. Planets beginning at different orbital distance and disc age will accrete different molecules. The aim of this thesis is to study the carbon to oxygen ratio of hot and cold Jupiter planets and see if any distinct relations are to be found. If so, it will allow future scientists to use the spectrum from a giant exoplanet’s atmosphere, find out the relative abundance of carbon to oxygen molecules, and use that to deduce what type of planet it is and how it has evolved. Since such spectra originate from the outer part of the planet, from the gas envelope, the analysis will be performed for the core and the gas envelope separately. A hot Jupiter planet has $M_{\text{env}} > M_{\text{core}}$ and a semi-major axis smaller than 0.1 AU. A cold Jupiter planet has $M_{\text{env}} > M_{\text{core}}$ as well, but its semi-major axis is larger than 1 AU (Bitsch et al., 2015b).

The initial growth-tracks that are the basis for this study has been produced in a
detailed disc evolution model (Bitsch et al., 2015a), which is described more thoroughly in Chapter 2.1. In order to deduce the chemical composition of the planets in each step of their formation, condensation temperatures and volume mixing ratios for the various chemical species in the disc are adopted from Madhusudhan et al. (2014). I choose to use volume mixing ratios adopted from observations of ice and gas in protoplanetary environments for all parts, and then I redo the last part with the volume mixing ratios based on theoretical calculations of a solar composition disc. The temperature for every set of semi-major axis and disc age was based on Bitsch et al. (2015a) and provided by the supervisor. It was used to visualize how the different ice lines are positioned and where and when the different types of planets cross them.

The structure of this paper is as follows. In section 2 I will describe the protoplanetary disc model and give a background theory on the subjects of planet migration and pebble/gas accretion. In section 3 the methods used in this thesis will be described. I will present the initial growth-tracks in section 4.1. In section 4.2 the position of the ice lines and the growth tracks, as a function of semi-major axis and disc age, will be plotted on top of a temperature contour plot to better see what type of molecules each planet will accrete. The evolution of the masses of each present species will then be plotted in section 4.3 for both the core and the gas envelope. The ratio of carbon to oxygen in the core and envelope will be presented in section 4.4 and 4.5 for the two different volume mixing ratios, see Figure 3.1. In section 5 I will summarize the work that has been done, discuss the most important results and take up possible future studies that could further improve my results.
Chapter 2

Background theory and modeling a planetary disc

2.1 The protoplanetary disc model

The most commonly used disc model is the Minimum Mass Solar Nebula (MMSN), originally presented by Weidenschilling (1977b) and Hayashi (1981). It is a protoplanetary disc with solar abundance that contains the minimum amount of mass needed to form the eight planets of the solar system. In this model the planets are assumed to form in situ, something that has later been proved to be incorrect, aside from some special cases where the planets are usually positioned at great orbital distances. In the year of 2005 another model was constructed called the ”Nice model” (Gomes et al., 2005; Morbidelli et al., 2005; Tsiganis et al., 2005), which was successful in explaining several features of the solar system. It suggests that the four giant planets were positioned close to each other just after the dissipation of the solar nebula and that the present structure of the solar system is the result of a late global instability due to scattering of planetesimals in the Kuiper belt outside of Neptune’s orbit, see Figure 2.1. Based on the initial positions of the planets in the Nice model, Desch (2007) introduced a new MMSN where the profiles for temperature, gas scale height and density are simple power laws. The new MMSN did however not take into accounts planet migration. The protoplanetary disc model used to produce the initial growth tracks in this thesis is based on observation of accretion onto young stars and has significant differences to the MMSN.

The disc viscosity, which within the context of this model is used only as a heating parameter and not an evolution parameter, can be driven by turbulence that arises when ionized atoms and molecules interact with magnetic fields in the disc, referred to as MRI (magnetorotational instability, see Balbus & Hawley, 1991). The disc viscosity is treated in the α-approach of Shakura & Sunyaev (1973). The equation for viscosity in the α-approach is \( \nu = \alpha H^2 \Omega_K \), where the \( \alpha \) parameter represents how efficient the turbulent transport is, \( H \) is the height of the disc and \( \Omega_K \) is the Keplerian frequency. In many models the value for \( \alpha \) vary inside the disc, since cosmic rays and X-rays make the ionization very much
more efficient in the upper disc than in the inner disc. However, there are other sources of turbulence that might be effective in the inner regions of the disc. Since the viscosity in the midplane is a bit unknown, the value for $\alpha$ in this model was set to be a constant with value $\alpha = 0.0054$.

The gaseous component of the protoplanetary disc is pressure supported, resulting in an orbital velocity that is smaller than the free orbital velocity. Solid bodies are not supported by this pressure and their orbital motion will be affected differently depending on their size. Small dust particles are strongly coupled to the gas and move with it, while large planetesimals are unaffected by the gas. Pebbles on the other hand will feel a strong headwind when moving through the gas. This results in a sub-Keplerian velocity of the pebbles and they will spiral inwards towards the central star, causing a mass flow through the disc (Weidenschilling, 1977a). The equation for the mass flux through the disc is

$$\dot{M} = 3\pi\alpha H^2 \Omega_K \Sigma_G,$$ \hspace{1cm} (2.1)

where $\Sigma_G$ is the gas surface density (Bitsch et al., 2015a). The mass flux is assumed to be constant at each orbital distance, however, over time it will drop from being in the order of $10^{-6} M_\odot/\text{yr}$ to $10^{-9} M_\odot/\text{yr}$ and the gas surface density will follow the trend (Hartmann et al., 1998). This drop will not happen linearly but faster at early stages in evolution. For a very shallow mass flow, the disc will be rapidly cleared by photoevaporation (Alexander et al., 2014). Photoevaporation is nevertheless not included in the model and the simulations are assumed to end after 3 Myr when the accretion rate has dropped to $2 \times 10^{-9} M_\odot/\text{yr}$. 

Figure 2.1: This figure is a reproduction of Figure 1 from Tsiganis et al. (2005), it shows the evolution of the four giant planets as predicted from the Nice model. U, Uranus; N, Neptune; S, Saturn and J, Jupiter. The top and bottom curve belonging to each planet is the maximum and minimum heliocentric distances, $Q$ and $q$, and the middle one is the semi-major axis, $a$. The maximum eccentricity of each planet is noted in the plot. The dashed line shows were Jupiter and Saturn crossed 1:2 mean motion resonance, the subsequent planet-disc interactions led to the current position of the planets.
Figure 2.2: This figure is a reproduction of Fig. 2 from Bitsch et al. (2015a). It shows the aspect ratio for a disc with $\dot{M} = 3.5 \times 10^{-8} M_\odot/\text{yr}$ and for the MMSN and the CY2010 model. The bump in aspect ratio occurs due to a transition in opacity.

The temperature of the disc can be computed with the following equation from Bitsch et al. (2015a)

$$T = \left( \frac{H}{r} \right)^2 \frac{GM_* \mu}{r R}$$

(2.2)

where $r$ the semi-major axis, $G$ the gravitational constant, $M_*$ the stellar mass, $\mu$ the mean molecular weight and $R$ the gas constant. Unlike the MMSN, which is optically thin and only features stellar heating, this disc model feature both stellar and viscous heating. The temperature of the inner disc is dominated by viscous heating, while stellar irradiation is responsible for keeping the outer part of the disc flared. The presence of these two heating processes give rise to dips and bumps in the disc profile that are not present in the MMSN, see Figure 2.2.

The dips and bumps arise at the ice line, at $T \approx 170$ K, where ice grains that crosses over to warmer regions sublimate and get subsequently smaller. Due to this, there will be more solid material present outside of the ice line, and hence the opacity will be higher there, than inside of it. In this region where the opacity decreases, photons will easier escape resulting, locally, in a more efficient cooling rate. This will lower the local temperature gradient and make it shallower than the one outside the ice line, creating an inflection in the temperature profile around the ice line. When the temperature decrease outwards the disc aspect ratio $\frac{H}{r}$, which usually increase radially, will follow, see 2.2. Recalling that the mass flux is constant, then a radial decrease of $\frac{H}{r}$ must be followed by a radial increase of $\Sigma_G$, resulting in a bump in the surface density profile. These bumps and dips in the different profiles will show to have important implications for planet formation, as particles concentrate there. Another consequence is that the temperature beyond the ice line, and thus the aspect ratio, will decrease as a result of the stellar irradiation being absorbed by the bumps (Bitsch et al., 2015a), something that can greatly affect planet migration.
At late times of disc evolution the viscous heating, proportional to $\Sigma_{G}$, drops fast while the stellar heating, dependent on the stellar evolution, decreases less, keeping the temperature of the outer disc fairly constant through the evolution. As the disc becomes colder the ice line moves closer to the star, and in late times there are no transitions in opacity present inside the computed domain (since the part of the protoplanetary disc that is closest to the star is assumed to be truncated by the star’s magnetic field, the simulations will be ended if a planet retains an orbital radius lesser than 0.1 AU). When particles grow to $>\text{mm}$ size they will no longer contribute to the opacity and thus if pebble growth is efficient, the opacity can be greatly reduced (Bitsch et al., 2015a). The temperature of the protoplanetary disc is also very much dependent on the abundance of heavy elements, $Z$. A low $Z$ will cause the opacity to decrease, resulting in a more efficient cooling rate and thus a cooler disc.

Further on the used disc model does not include perturbers such as planets, excluding effects such as mean-motion resonance between planets. The simulations begin with a planetary embryo that has a mass corresponding to the transition mass, which is the planetary mass where pebble accretion begins to occur from the Hill radius and not the smaller Bondi radius (Lambrechts & Johansen, 2012), at the distance where it is initially positioned. The pebble transition mass can be calculated as

$$M_{t} = -\sqrt{\frac{1}{3} \frac{(\eta v_{K})^3}{G \Omega_{K}}}.$$  

(2.3)

where $v_{K} = \Omega_{K} r$ is the Keplerian velocity and $\eta = -\frac{1}{2} \left( \frac{H}{r} \right)^2 \frac{\sin \varphi}{4 \Omega r}$ is a measure of the gas pressure support (Bitsch et al., 2015b). All core growth will be due to the accretion of pebbles and the possible accretion of planetesimals is not included. The simulations will end after the disc has reached an age of $3 \text{ Myr}$ or when the planet comes closer to the star than 0.1 AU. Further information and detailed descriptions of the protoplanetary disc can be found in Bitsch et al. (2015a).

### 2.2 Planet migration

The orbital evolution of a planet is dominated by interactions between the protoplanetary disc and the growing planets in it. In real discs planet-planet and star-planet interactions also play a major role, but since perturbers are not included in this model, at least the planet-planet interactions are neglected.

#### 2.2.1 Planet-disc interactions of low mass planets – Type I migration

Interactions between the protoplanetary disc and planets that are still embedded in it occur mainly via gravity. If the planets are of low mass, then the gravitational perturbations on the disc caused by these planets are small, and since the migration will be slow, the
perturbations due to the radial movement of the planet can be neglected. Such planets are in the regime of type I migration (Baruteau et al., 2014), and the perturbations in the disc can be split into 2 parts, where one part is responsible for the wave torque (also known as the Lindblad torque) and the other one for the corotation torque.

At certain locations in the disc where the azimuthal velocity of the gas relative to the planet matches the phase velocity of acoustic waves in the azimuthal direction, referred to as Lindblad resonances (Goldreich & Tremaine, 1979, 1980), planets that exert a gravitational force on their parent disc can launch waves that when superpositioned give rise to a one-armed spiral density wave called the wake (Ogilvie & Lubow, 2002), see Figure 2.3. The inner wake give rise to a positive torque on the planet and equivalently give angular momentum to the planet, the opposite holds for the outer wake. The sum of these torques is called the Lindblad torque, $\Gamma_L$, and has a size and sign that depend linearly on the negatives of the local power law exponent of the surface density and the temperature ($\Sigma \propto r^{-\alpha}, T \propto r^{-\beta}$) through the following relation by Paardekooper et al. (2010)

$$\gamma \frac{\Gamma_L}{\Gamma_0} = -2.5 - 1.7\beta + 0.1\alpha,$$

(2.4)

where $\gamma$ is the ratio of specific heats and $\Gamma_0$ is a normalization torque that is proportional to $(\frac{\dot{M}}{r})^{-2}$. In general we expect $\alpha, \beta > 0$ and for normal values of $\alpha$ this will yield $\Gamma_L < 0$. A negative torque exerted on the planet will decrease it’s orbital angular momentum and result in inward migration.

The other type of torque acting on the planet is due to material that on average corotates with it, the corotation torque, $\Gamma_C$. For an isothermal disc the corotation torque scales with the local gradient in vortensity, which is vorticity divided by surface gravity (Goldreich & Tremaine, 1979), yielding a higher dependence upon surface gravity gradients than the wave torque. These gradients have a shallower profile resulting in a more positive torque, but since the wave torque dominates the corotation torque except for in cases of extreme density profiles (Tanaka et al., 2002), the sum of them will normally be less than zero. Paardekooper et al. (2010) derived a formula for the linear corotation torque in a non-isothermal disc (the isothermal case can be obtained by letting $\xi = 0$)

$$\gamma \frac{\Gamma_{C,\text{linear}}}{\Gamma_0} = 0.7 \left( \frac{3}{2} - \alpha - \frac{2\xi}{\gamma} \right) + 2.2\xi,$$

(2.5)

where $\xi = \beta - (\gamma - 1)\alpha$ is the negative of the local power law exponent of the specific entropy.

Another expression for the corotation torque can be obtained by considering the torque on a planet due to disc material executing horseshoe turns relative to the planet, the so-called horseshoe drag, see Figure 2.4. When material makes such a turn, fluid elements move between regions of different vortensity and since the overall vortensity must be conserved this dictates that the surface density must change, which results in a torque being applied on the planet (Ward, 1991). This torque was derived by Paardekooper et al. (2010)

$$\gamma \frac{\Gamma_{C,\text{HS}}}{\Gamma_0} = 1.1 \left( \frac{3}{2} - \alpha \right) + 7.9\frac{\xi}{\gamma},$$

(2.6)
the first part is vortensity-related and the second entropy related. The entropy related part arise since conservation of momentum during a horseshoe turn leads to a jump in entropy along the separatrices of the horseshoe region whenever there is a radial gradient of entropy in the disc. These jumps in entropy act as a source of vorticity which results in a torque being exerted on the planet (Baruteau et al., 2014). If this entropy related part is very strong it could result in a corotation torque that is strong enough to counterbalance the wave torque and yield $\gamma \frac{L_{\text{obs}}}{L_p} > 0$, resulting in outward migration. Paardekooper & Papaloizou (2009) showed that whenever a horseshoe turn takes place $\Gamma_{C,\text{linear}}$ gets replaced by $\Gamma_{C,\text{HS}}$, unless $\alpha$ takes a very strong value.

Since there are no waves involved in the corotation torque it requires a constant flow of angular momentum into the horseshoe region to maintain unsaturated, unlike the wave torque. This flow of angular momentum is, as previously mentioned, probably due to turbulence arising from MRI. MRI enhance present magnetic fields and are linked to the observation of launched jets in protoplanetary discs. It also drives MHD turbulence which excites density waves that causes a new fluctuating component of the torque which is driven by the turbulence and not the planet itself. This torque which is independent of the planet mass, unlike the previously mentioned ones, dominate the orbital evolution of low-mass objects such as planetesimals and can result in outward migration even though type-1 migration is directed inwards (Baruteau et al., 2014).
2.2.2 Planet-disc interactions of massive gap opening planets – Type II migration

If the torque exerted on the disc by the planet is larger than the viscous torque responsible for disc spreading in absolute value, this will result in an annular gap being carved around the orbit of the planet (Lin & Papaloizou, 1986a). The criteria for a gap with a density lower than 10% of the rest of the disc to open up was determined by Crida et al. (2006) and is

$$P = \frac{3H}{4r_H} + \frac{50}{qR} \leq 1,$$

(2.7)

where $P$ is a dimensional constant, $R = \tau_p^2 \Omega_p/v$ is the Reynolds number and $v$ is the kinematic viscosity of the disc. The minimum planet-to-star ratio, $q_{\text{min}}$, that satisfies this condition can be obtained by setting $P$ to be 1 and is given by

$$q_{\text{min}} = \frac{100}{R} \left[(X + 1)^{1/3} - (X - 1)^{1/3}\right]^{-3},$$

(2.8)

for $X = \sqrt{1 + 3Rh^3/800}$ where $h = H/r$ (Baruteau et al., 2014). Since $h$ generally increases with orbital radius the planet-to-star ratio needed to open up a gap does so as well.

The protoplanet's tidal torque transfer the disc material that is initially positioned in the gap to the surrounding regions. The planet then adjust its position to the center of the gap, so that the angular momentum transfer rate from both sides of it is precisely balanced. At this phase the planet will continue to migrate with the viscous accretion speed of the disc, this is called type II migration. This accretion is slower than type I migration and can be slowed down even more if the planet is much more massive than the mass of the gas
out outside the gap. If this occur then the outer disc will be held by the planet while the inner disc continues to migrate with the previous speed, leading to a partial or total depletion of the inner disc. At the outer edge of a gap there will be a pressure maximum where particles that have been decoupled from the gas accumulate (Baruteau et al., 2014), this can act as a sweet spot for planet formation.

2.3 Pebble accretion and gas accretion

The growth of a planetary core by the accretion of pebbles of mm–cm size is an effective process. The accretion speed depends on several factors, including on whether the planet’s Hill radius is larger or smaller than the scale height of pebbles. The scale height of pebbles is calculated as

\[ H_{\text{peb}} = H_{\text{gas}} \sqrt{\alpha / \tau_I}, \quad (2.9) \]

where \( \alpha \) is the viscosity parameter and \( \tau_I \) is the Stokes number of the particles (Youdin & Lithwick, 2007). If the planet’s Hill radius exceeds the scale height of pebbles, that is if the planet accretes all pebbles that drift towards the star at that orbital distance, it will accrete in a 2D fashion,

\[ M_{\text{c,2D}} = 2 \left( \frac{\tau_I}{0.1} \right)^{2/3} r_H v_H \Sigma_{\text{peb}}, \quad (2.10) \]

where \( r_H = r [M_c/(3M_*)]^{1/3} \) is the Hill radius, \( v_H = \Omega_H r_H \) the Hill speed and \( \Sigma_{\text{peb}} \) the pebble surface density (Bitsch et al., 2015b). If \( \tau_I > 0.1 \) the equation reduces to

\[ M_{\text{c,2D}} = 2 r_H v_H \Sigma_{\text{peb}}, \quad (2.11) \]

since the planetary embryo cannot accrete particles from outside its Hill radius (Lambrechts & Johansen, 2012).

If the planet’s Hill radius is smaller than the scale height of pebbles, so that it does not accrete all pebbles drifting towards the star at that orbital distance, it will accrete in a 3D fashion, which is slower than the 2D accretion and related to it as

\[ \dot{M}_{\text{c,3D}} = \dot{M}_{\text{c,2D}} \left[ \frac{\pi (\tau_I/0.1)^{1/3} r_H}{2 \sqrt{2 \pi H_{\text{peb}}}} \right], \quad (2.12) \]

(Morbidelli et al., 2015). When and where the planet reaches the faster 2D accretion rate will greatly affect the final mass of the core, and is dependent on the particle size and the pebble scale height. The further out in the disc the planetary embryo is placed, the higher mass is needed to reach this faster 2D accretion, since the scale height of pebbles increase with semi-major axis (Bitsch et al., 2015b).

As mentioned in the introduction, planets begin to attract gas from the gas disc while growth of the core is still occurring. The reason why the gas does not fall down onto the planetary embryo, but settles in a gaseous envelope around it, is that pebbles falling down in the protoatmosphere deposit their potential energy above the surface of the core. This
provides the heat necessary to yield enough pressure to support the gas envelope. If pebble accretion was not hindered, this pressure support would be able to maintain an envelope up to that the mass of the envelope equals the mass of the core. Then the self-gravity of the gas will lead to a collapse of the envelope onto the core. However the core mass at which this usually happens is much higher than those core masses present in our solar system (Guillot, 2005). Luckily it turns out that pebble accretion is halted long before that, at the so-called pebble isolation mass (Lambrechts et al., 2014),

\[ M_{iso} \approx 20 \left( \frac{H/r}{0.05} \right)^3 M_\oplus. \]  

(2.13)

When the planet reaches its pebble isolation mass, it can perturb the gas disc enough to make the speed of the gas in a narrow ring just outside the orbit of the planet faster than Keplerian (Paardekooper & Mellema, 2006a; Morbidelli & Nesvorny, 2012). In this ring the action of the gas drag reverses and pebbles are pushed outwards, resulting in an accumulation of pebbles at the outer edge of the ring and no further accretion onto the planet. When pebble accretion ceases the pressure supporting the gas envelope disappears and the core begins to contract the envelope. During the relatively long contraction phase the core also attracts additional gas from the protoplanet disc. When the envelope grows massive enough to equal the mass of the core, runaway gas accretion sets in (Bitsch et al., 2015b). This continues until the dissipation of the gas disc.

The heavy dependence upon \( H/r \) means that planets beginning to form at large semi-major axis, need to migrate a significant distance before gas accretion onto the planetary core can set in. If they do not reach pebble isolation mass before the dissipation of the gas disc, they are stranded as ice giants. Planets positioned further in however can reach their pebble isolation mass even if they begin to form late in the disc lifetime. The initial semi-major axis and disc lifetime will thus greatly affect what type of planet is formed, if pebble isolation mass happens early in disc lifetime we get a gas giant, if not we are left with an ice giant. The final planetary mass as a function of initial orbital separation and disc age can be viewed in Figure 2.5 for two discs with different metallicity.
Figure 2.5: The two figures are reproductions of Fig.4 and Fig.5 from Bitsch et al. (2015b). They show the final planetary mass as a function of formation distance and formation time for two discs with different metallicity.
Chapter 3

Method

I was provided with 4 file-packages, each containing 4 or 5 growth tracks produced in the protoplanetary disc model of Bitsch et al. (2015a), in the beginning of the thesis work. Two of the file-packages contained growth tracks from simulations resulting in hot Jupiter planets, one where both the age of the disc and the initial orbital distance varied between the planets, and one where only the age of the disc differed. The two other file packages contained growth tracks from simulations resulting in cold Jupiter planets, one with a pebble metallicity of 1% (as in the above hot Jupiter planets) and one where it had been increased to 1.5%. Each growth track held information about the age of the disc [yr], the orbital separation [AU], the mid-plane temperature [K], the surface density of the disc [g/cm²], the mass of accreted solids [M_J], the mass of accreted gas [M_J] and the total amount of mass accreted [M_J] for every step in the evolution of the planet. The masses were later converted to earth masses [M_E] for convenience.

I imported the data packages into a python script and made one plot for every set of planets. Then I compared them in order to find out how initial orbital distance and disc age affects the mass and orbital evolution of a planet. In a previous version of the code, I marked the crossing of any iceline for every planet. This however turned out to yield quite messy plots and since the icelines will be visualized in other parts of the thesis, I decided to exclude them in the final version. For the sake of explanation, I made an additional plot showing the evolution of the total mass, the mass of the core and the mass of the envelope.

In order to better be able to visualize how the planets evolve in the disc, I produced contour plots showing the temperature for every set of semi-major axis and disc age. The temperature matrix that I used to make the contour plots is based on Bitsch et al. (2015a) and was provided by the supervisor and rewritten by me in python. I draw icelines for every molecule and plotted a number of growth tracks on top of the contour plot. I marked the end of core accretion on the growth tracks so that the content of the core and envelope in each planet can be easily inferred.

I calculated the chemical composition of the planets in each step of their evolution using condensation temperatures and volume mixing ratios from Table 1 in Madhusudhan et al. (2014), see Figure 3.1. The dominant carbon and oxygen bearing species in the disc midplane are listed to the left in Figure 3.1. There are two different sets of volume mixing
Figure 3.1: This figure is a snapshot of Table 1 from Madhusudhan et al. (2014). (a) The condensation temperatures for the above four molecules are adopted from Mousis et al. (2011) and the below two from Öberg et al. (2011). (b) Volume mixing ratios adopted based on theoretical computations of a solar composition disc (Woitke et al., 2009). (c) Volume mixing ratios adopted based on gas and ice observations in protoplanetary enviroments (Öberg et al., 2011).

In Table 1, we present the volume mixing ratios of various chemical species in the accretion disk. The table includes the species, their condensation temperatures, and their volume mixing ratios in different cases. The ratios in Case 1 account for the total abundance of the dominant carbon and oxygen-bearing species in a typical disc from a combination of ice observations. In Case 2, we consider the grain composition in the dense interstellar medium. In case 1, there are no carbon grains present in the disc, while for temperatures above 20K, there is no solid accretion of carbon. For temperatures higher than 70K, they propose that most oxygen is locked up in H2O, leaving carbon to form CH4 instead of CO. In case 2, there is no CH4 but there are carbon grains. The evaporation temperature for the carbon grains is unknown, and to prevent this unknown component from influencing the outcome too much, they use a high evaporation temperature. I used case 2 in Figure 3.1 for this part of the thesis. The elemental volume fractions for solar composition used for the volume mixing ratios in 3.1 are O/H = 4.9 × 10^{-4}, C/H = 2.7 × 10^{-4} and Si/H = 3.2 × 10^{-5} (Asplund et al., 2009). These were converted to mass fractions and then normalized so that the sum of all three mass fractions equaled 1, this is done since I do not investigate the accretion of H.

I multiplied the resulting mass mixing ratios for each molecule with the time derivative of the core mass in every step of the evolution, as long as the temperature was lower than the condensation temperature for the corresponding molecule. For higher temperatures, I multiplied the time derivative of the core mass with zero, implying no further core accretion of that molecule. I conducted the same procedure for the gas envelope but with zero accretion for temperatures lower than the condensation temperature. In order to obtain the total mass evolution for each molecule in a planet, I integrated the result with the trapezoidal method. I made plots containing the molecular mass evolution for both the envelope and the core for 4 hot Jupiter planets and 4 cold Jupiter planets.

Finally, I calculated the total mass of carbon from the relative amount of carbon in
each molecule and divided it by the total mass of oxygen. This was conducted for the core and envelope separately, in every step of the evolution. I then converted the mass ratio into a number ratio and plotted the result for two hot Jupiter planets and two cold Jupiter planets. I inferred the indexes corresponding to the crossing of any iceline from the temperature data of each planet and marked it on the plots. I conducted this last part for both sets of volume mixing ratios in Figure 3.1.
Chapter 4

Presentation of results

4.1 Evolution of total mass

The top left plot in Figure 4.1 shows simulations that resulted in hot Jupiter planets. All growth tracks begin with mass accretion taking place approximately in situ. After a while the planets begin to migrate through the disc and the growth tracks flatten out. This flattening occurs when the accretion of solids stop, at the pebble isolation mass. When the pebble isolation mass is reached there is an increase of gas accretion, however this increase is too small to be noticeable in the plot for total mass. After a period of migration, where the total mass of the planet does not change significantly, there is a sudden increase in mass accretion. This sudden increase in mass accretion is the onset of runaway gas accretion, occurring when the mass of the envelope equals the core mass. All these features can be seen in Figure 4.2. When the three outermost planets are compared, it is clear that the planet beginning at the largest semi-major axis needs to migrate the furthest distance before rapid gas accretion can set in. The same planet also has the largest mass at the beginning of the simulations, this is since the initial mass is determined by the transition mass. The innermost planet gets trapped in a region of outward migration when it reaches a mass of $\approx 5 \, M_{\oplus}$ and a has semi-major axis of $\approx 4 \, AU$. It outgrows this region when it reaches a mass of $\approx 9 \, M_{\oplus}$. The planet beginning at semi-major axis $4.2 \, AU$ never gets trapped in this region since it starts at a later disc evolution time and has a slightly bigger initial semi-major axis, compare with Figure 1.2.

The top right plot in Figure 4.1 shows hot Jupiter planets that has the same initial semi-major axis but begin at different disc evolution times. Since the mass flow through the disc decrease with time, it is reasonable to believe that planets beginning early in disc evolution time needs to migrate a smaller distance before the onset of runaway gas accretion, and thus get larger than planets beginning at late disc evolution time. As one can see in the plot, this is however not the case. The left plot in Figure 2.5, which is a reproduction of Fig. 4 from Bitsch et al. (2015b), shows the final mass of planets as a function of formation distance and formation time, in a disc with $Z = 1\%$. The final planetary masses in the top right picture in Figure 4.1 matches the ones that are expected
Figure 4.1: These figures show the initial growth-tracks that have been plotted using data from the modeled protoplanetary disc, described in section 2.1. Here it is the evolution of the total mass as a function of semi-major axis that has been plotted for the different planets. The initial disc evolution time for each planet is specified in the plot along with the initial semi-major axis when it differs between the planets.

from the left plot in Figure 2.5. The planet with $t_0 = 1$ Myr and $r_0 = 10$ AU start in a part of the disc where the aspect ratio, $H/r$, is big, resulting in large core masses. Such planets become too massive to stay in the regions of outward migration and therefore reach 0.1 AU before they grow more massive than $300 M_{\oplus}$ (Bitsch et al., 2015b). Consequently, they get less massive than planets beginning at the same formation distance but at later formation time, when the aspect ratio is smaller.

The two bottom plots in Figure 4.1 show simulations of cold Jupiter planets. For these planets, the increase in gas accretion when the isolation mass has been reached is easily noticeable in the growth tracks. The metallicity in pebbles has been increased by 0.5% in the right plot to see if it results in any substantial differences. In the right plot in Figure 2.5, the final planetary mass is plotted for a disc with $Z = 1.5\%$. The increase in metallicity allows for planets to begin formation at later disc evolution times and at a
Figure 4.2: The figure shows a zoomed in part of a plot where the evolution of the total mass, the mass of the gas and the mass of the core has been plotted for a hot Jupiter planet beginning at semi-major axis 12.8 AU.

larger semi-major axis, but still reach the same final mass as in a disc with $Z = 1\%$. In Figure 4.1 the initial age of the disc for the planets in the bottom right plot has indeed been increased compared to the planets in the bottom left plot, but apart from that there is no substantial difference between the two plots, implying that pebble accretion has a low sensitivity to changes in the pebble metallicity.

4.2 Icelines

In Figure 4.3 and 4.4 the migration of the icelines are clearly visible. The icelines move substantially closer to the star as the disc gets older and the stellar heating decreases. This has important implication for planet formation, since planets beginning at the same semi-major axis but at different disc age will begin to accrete the same molecules at different semi-major axis. For example, a planet beginning at 10 AU when the age of the disc is 2 Myr will begin to accrete CO$_2$ at a distance of approximately 2 AU from the central star (see Figure 4.3), while a planet beginning at the same semi-major axis when the age of the disc is smaller than 0.5 Myr will begin to accrete CO$_2$ after only a small period of migration. If the two planets reach the same final semi-major axis and non of them is trapped in outward migration, this will result in a larger abundance of CO$_2$ in the planet beginning at earlier disc evolution time. Other molecules, like Si, will only be present in planets that begin to form at early disc age and migrate fast.

Although core accretion continues for a significant amount of time, it takes place approximately in situ. While comparing the different planets, it is evident that planets beginning early in disc evolution time and far out in the disc need to migrate a large distance before pebble isolation mass is reached, as expected. Since no ice line is crossed during core accretion for the hot Jupiter planets, the relative abundance of molecules in
Figure 4.3: The contour plot shows the temperature as a function of semi-major axis and disc age. The icelines for different molecules have been drawn onto it along with the growth-tracks for the same four hot Jupiter planets as in Figure 4.5. The dashed line represent the core and the solid line the gas envelope. The dot on the growth-tracks represent the end of pebble accretion.

Figure 4.4: The contour plot shows the temperature as a function of semi-major axis and disc age. The icelines for different molecules have been drawn onto it along with the growth-tracks for the same four cold Jupiter planets as in Figure 4.6. The dashed line represent the core and the solid line the gas envelope. The dot on the growth-tracks represent the end of pebble accretion.
CHAPTER 4. PRESENTATION OF RESULTS

Figure 4.5: These four figures show the chemical evolution of the core and envelope for 4 hot Jupiter planets with Z=1% that are being implanted at different semi-major axis. The dashed lines represent the core and the solid lines the gas envelope.

the cores of these planets should be the same, except for the innermost planet that lack CO₂ in its core. This could be inferred from Figure 4.5 as well. Ignoring the outermost planet in Figure 4.4, no icelines are crossed for the cold Jupiter planets, indicating that the relative abundance of molecules in those planets should be very similar.

4.3 Evolution of chemical species

The growth tracks for hot Jupiter planets begin well inside the CO iceline, and therefore there is no CO molecules in the core of hot Jupiter planets. The core of the top left planet beginning at semi-major axis 4 AU does not accrete any CO₂ molecules, but ignoring that, the composition of hot Jupiter planets is very homogeneous. H₂O is the dominant molecule in the core, and the total mass of H₂O in the core is around half an order of magnitude higher than the mass of any other core molecule. The gas accretion of CO molecules is ongoing during the entire evolution and CO becomes the most abundant molecule in the
Figure 4.6: These four figures show the chemical evolution of the core and envelope for 4 cold Jupiter planets with Z=1%, that are being implanted at different semi-major axis. The dashed lines represent the core and the solid lines the gas envelope.

gas envelope, followed by $\text{H}_2\text{O}$. If the $\text{H}_2\text{O}$ iceline would have been placed at larger semi-major axis it would have resulted in $\text{H}_2\text{O}$ being the most abundant molecule in the gas envelope.

The cold Jupiter planets in Figure 4.6 has a lower maximum temperature than 70K and therefore only contain CO in their gas envelopes. Ignoring the bottom right picture, in which the growth track passes over the CO iceline towards colder temperatures, the relative amount of molecules in the core is the same independent on the initial semi-major axis. This is always the case if no icelines are crossed and if the accretion rates are independent of the planet itself or age of the disc. The planets begin to migrate through the disc before the accretion of solids has ceased, this migration phase is longer than for the hot Jupiter planets. This is expected since the pebble isolation mass increase as the cube of the aspect ratio, and the planets in Figure 4.6 begin at a substantially larger semi-major axis than the planets in Figure 4.5.
Figure 4.7: These four figures show the number ratio of carbon to oxygen in the core (dashed line) and in the envelope (solid line). The dots represent the different ice lines that the planet migrates over. The two lower plots represent cold Jupiter planets with $Z = 1\%$ beginning at 21.5 respectively 33.2 AU and the two above represent hot Jupiter planets beginning at 4.0 respectively 12.8 AU. The sudden increases/decreases in the number ratio is due to the crossing of an ice line.

### 4.4 Carbon to oxygen ratio - case 2

Depending on which iceline a planet crosses over, the C to O ratio increases, decreases or remains unaffected. For hot Jupiter planets, the C to O ratio decreases when the CO$_2$ iceline is crossed. Later, the existence of carbon grains in the disc brings the number ratio of the envelope up a bit. However, once the water ice line has been crossed the number ratio quickly decreases. Both hot Jupiter planets in Figure 4.7 has a number ratio of around 0.7 for the envelope when the simulations are ended. The number ratio for the core stays the same throughout the evolution but is slightly lower for the inner planet, the reason for this is that the inner planet accretes CO$_2$ to the core during a period, which brings the C to O ratio down.

For cold Jupiter planets that does not cross over any ice lines, the number ratio should
stay the same throughout the evolution (recall that CH$_4$ is not present in the disc). Since the only molecule accreted to the envelope is CO, the number ratio will be equal to one for the gas envelope. The core accretes many different molecules and has a number ratio lower than one. The number ratio for the core can be substantially increased if the planet has a minimum temperature smaller than 20 K, as seen in the bottom right plot in Figure 4.7.

By looking at a spectrum from a hot Jupiter atmosphere one can deduce the relative abundance of carbon to oxygen in it. When that has been performed one could use my results to tell something about how the planet has evolved. If the number ratio is equal to one and the planet is found a couple of AU from the host star, then the planet is most likely a cold Jupiter planet that did not accrete any molecules containing C or O except for the CO molecule. Such a planet has most likely had a large initial semi-major axis and/or begun formation at late disc evolution time. If a planet is found much closer to the star and still has a number ratio of one, then it is most likely a cold Jupiter planet that continued to migrate by interacting gravitationally with another planet or a binary star after the dissipation of the gas disc. If one were to find a planet with a number ratio of approximately 0.7 that is positioned not too far from the star, then it is likely a hot Jupiter planet. This planet has then either had a rather small initial semi-major axis or begun formation in early disc evolution time. If a planet with the same number ratio were to be found at a larger distance from the star, it may have migrated outwards either after of during the lifetime of the protoplanetary disc. If it would have been during the disc lifetime, then the number ratio would probably have been affected though.

As of today there exist no method for measuring the number ratio of the core. However, if one were to measure it then it would probably be around 0.2 as in Figure 4.7. If a planet is found where the ratio is higher than this, and especially if it is found far out, it might be the case that the CO iceline has moved inwards faster than the planet and passed it, as in the bottom right plot in Figure 4.7.

4.5 Carbon to oxygen ratio - case 1

The effects of using case 1 in Figure 3.1 for the volume mixing ratios instead of case 2 are substantial. Unlike in case 2, no carbon grains are present in the disc, but there is CH$_4$. The CH$_4$ volume mixing ratio is more than two times larger than the volume mixing ratio for carbon grains, and the gas accretion begins further out from the central star. This should result in higher number ratios for envelopes of hot Jupiter planets, in at least part of their evolution. The CO volume mixing ratio is higher than in case 2 for temperatures lower than the CO$_2$ condensation temperature, but lower for temperatures above it. There is no solid accretion of CH$_4$ or CO$_2$, so for temperatures higher than 20 K, no carbon is accreted to the core.

When the plots in Figure 4.8 are investigated, one immediately notices that the number ratio of the cores for planets with minimum temperature higher than 20 K is zero throughout the evolution, as expected. This is very different from the number ratios achieved in
Figure 4.8: These four figures show the number ratio of carbon to oxygen in the core (dashed line) and in the envelope (solid line). The dots represent the different ice lines that the planet migrates over. The two lower plots represent cold Jupiter planets with $Z = 1\%$ beginning at 21.5 respectively 33.2 AU and the two above represent hot Jupiter planets beginning at 4.0 respectively 12.8 AU. The volume mixing ratios used are those from case 1b in Figure 3.1.

Figure 4.7: The planet that has a lower minimum temperature than 20 K get a slightly lower number ratio than in Figure 4.7. The reason for this is that no CO$_2$ exist that lower the H$_2$O volume mixing ratio. The number ratio of the envelopes belonging to the cold Jupiter planets are the same as when case 2 was being used, this is since CO is the only molecule that is being accreted.

The two above plots in Figure 4.8 has an evolution of the number ratio for the gas envelopes that differ a lot from in Figure 4.7. The hot Jupiter planet beginning at semi-major axis 4 AU has an initial envelope number ratio just above 1.5, due to the efficient CH$_4$ accretion. When the planet migrate outwards past the CO$_2$ iceline, the accretion of CH$_4$ ends, resulting in a quick decrease of the number ratio. Later when the planet migrate inwards past the CO$_2$ iceline, the accretion of CH$_4$ sets in once again. The gas accretion of CO$_2$ should bring the number ratio down, but since the accretion of CH$_4$ is more efficient...
it will instead increase again. When the water iceline is passed, the number ratio quickly decreases, similar to when case 2 was being used. The hot Jupiter planet beginning at orbital distance 12.8 AU has an initial number ratio of unity. When the CO$_2$ iceline is passed, the accretion of CH$_4$ brings the number ratio up to a little less than 1.5. When the water iceline is passed the number ratio decreases and the final number ratio is around 0.7.

When comparing the two Figures 4.7 and 4.8, there is one thing that I myself find particularly interesting. It is that, even though the evolution tracks for the number ratios of the envelopes look very different in some plots, the final value is almost exactly the same. The inclusion of CH$_4$ accretion greatly enhances the C to O number ratio and dominates the evolution of the number ratio for temperatures between 70 and 170 K. For temperatures higher than 170 K, H$_2$O accretion dominates. A more efficient CH$_4$ accretion, a less efficient accretion of H$_2$O or the inclusion of carbon grains are modifications that could result in a final value for the number ratio above unity. If the gas disc were to disperse before the planet has migrated to an orbital distance smaller than 0.1 AU, number ratios higher than unity could also be found.
Chapter 5

Summary

In this work I present different plots showing how the mass evolution and molecular evolution look like for different types of planets. The initial data has been produced in a detailed model of a protoplanetary disc that is quite different compared to the commonly used MMSN. In this disc model, the simulations begin with a planetary embryo that has a mass corresponding to the transition mass at the initial semi-major axis, and further core growth is only due to the accretion of pebbles. Gas that is accreted onto the planet while pebble accretion is still ongoing settles in an envelope around the core. When the pebble isolation mass has been reached, the accretion of pebbles is halted and the gas envelope can be contracted. When the mass of the gas envelope equals the mass of the core, runaway gas accretion sets in. This continues until the simulations are ended, which happens when the planet comes closer to the star than 0.1 AU or when the disc has reached an age of 3 Myr.

In Figure 4.7 and Figure 4.8 I show that hot Jupiters have a carbon to oxygen ratio of around 0.7 in their gas envelopes, independent on whether theoretically adapted volume mixing ratios or volume mixing ratios adapted from observations of protoplanetary environments are used. In the same figures I find that cold Jupiters have an equal amount of carbon and oxygen in their gas envelopes.

The cores of hot and cold Jupiter planets are heavily oxygen dominated. If a planet happens to accrete CO to its core during part of its evolution, that increases the carbon to oxygen ratio. Planets that begin formation very far out in the protoplanetary disc might therefore have less oxygen dominated cores than planets beginning closer to the central star.

Based upon these results I suggest the carbon to oxygen ratio as a future method for separating between the two formation paths of hot Jupiters. If the number ratio of the gas envelope in a hot Jupiter planet is 0.7, then the planet has migrated inwards during formation due to gravitational interactions with the disc. If the number ratio is 1, then the planet has formed further out in the disc and been scattered inwards later due to disc-free interactions.

Future studies could include the accretion of planetesimals in the model and see how it affects the results. Some of these planetesimals would land on the core while others would
be destroyed in the atmosphere. The solids that get deposited when the planetesimals are destroyed in the atmosphere could sink down to the core or remain in the atmosphere. Depending on where these planetesimals have been formed, they will have different chemical composition and thus affects the carbon to oxygen ratio differently. If the planetesimals are composed of mostly water ice they will bring the ratio down. The net effect would probably not be very drastic however, considering that pebble accretion is very much more efficient then planetesimal accretion. Another aspect one could consider is the accretion of dust grains. Also, the constant $\alpha$ that is used when calculating the disc viscosity, could be a subject of further investigation. There seem to be many different physical processes affecting the viscosity within the disc, and it is likely to believe that a more accurate protoplanetary disc model can be achieved if a more detailed description for $\alpha$ is used.
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