



## 1. INTRODUCTION

Two big questions. In the context of core accretion:  
- where in the disk can you form Gas Giants? - what

compositions will the formed Gas Giants obtained?

we can learn about this through a combination of studying planet formation in protoplanetary disks, and the end-results of planet formation, i.e. exo-planets and the architecture and composition of our own Solar System

1. Protoplanetary disks 1a. Density and temperature structures 1b. Chemical processes and structures
2. Observational constraints on Gas Giant formation and compositions
3. Core accretion formation of planets and its challenges
4. Interactions between disk physics and chemistry, and core accretion
5. Connection between disk compositions and the compositions of nascent planets

In recent years, the field of giant planet formation has aimed to answer two fundamental questions:

1. Where in the protoplanetary disk can gas giants form?
2. What compositions will the formed giant planets have obtained?

We can start uncovering the answers to these questions through a combination of studying planet formation in protoplanetary disks, the end-results of planet formation (i.e., exoplanets), and through comparisons with the architecture and composition of our own Solar System. Within the last two decades, more than one thousand extrasolar planets (exoplanets) have been discovered. Their diversity in terms of mass, radius, location and composition provides an exciting field of research, with the eventual goal of finding planets that are similar to our own Earth and may sustain life. For this purpose, it is thus crucial to explore and understand how planets obtain their compositions. Observations of Earth-like planets that can provide useful insight about their composition are challenging the solid interior structure of terrestrial planets cannot be detected, and their gaseous envelopes are small by comparison (both in mass and radius), which makes it difficult to obtain atmospheric spectra and find out what chemical compounds they are made of. We therefore turn to giant planets, which have provided a rich and intriguing research area for decades. Gas giants contain most of their mass in their atmosphere, hence their chemical composition is determined by that of their envelopes. The last few years have seen a substantial increase in the number of giant planets with observed atmospheric spectra (e.g.,  $\text{Jupiter}$ ,  $\text{Saturn}$ ), which has enhanced our understanding of these planets chemical structure, and has provided us with quantitative information about the abundances of various compounds in their envelopes besides hydrogen and helium. Finally, gas giants shape the architecture of planetary systems and affect the delivery of volatile compounds to terrestrial planets, which has direct consequences for the habitability of worlds similar to our own. Thus testing theories of planet formation against gas giant compositions will help constrain planet formation theories more generally.

Both terrestrial and giant planets are born in protoplanetary disks, which implies that their compositions

are determined by and tightly linked to the structure and composition of the disk. The chemical and dynamical evolution of disks, as well the formation of giant planets have both been previously investigated in isolation. However, the coupled chemo-dynamical disk evolution, planet compositions, and most importantly the disk-planet connection have not yet been considered in detail. In this thesis, I uncover some of the answers to this issue from two standpoints: (1) by looking at the role of disk location in setting the conditions for the formation of wide-separation gas giants, and (2) by investigating how the structure and chemical composition of the protoplanetary disk at different radii affects the composition of nascent giant planets.

### 1.1. *The Role of Disk Location in Setting the Minimum Core Mass for Giant Planet formation*

- Gas giants are largely believed to form through core accretion (insert core accretion sketch from various talks). This process is particularly challenging in the outer disk due to long dynamical timescales. At the same time, wide separation gas giants have been discovered (HR 8799 plot). This poses an intriguing question: how do these planets form: I answer this question in the first part of my thesis; specifically I calculate the minimum  $M_{\text{crit}}$ , which applies when cores no longer accrete solids. Standard core accretion studies are not built to properly explore this  $M_{\text{crit}}$ . Here explain standard core accretion studies in more detail and insert e.g. one of the Mass vs time figures from Pollack et al. 1996. Explain how our study is different. Finalize by saying that the studies I performed clearly challenge previous claims that core accretion cannot operate at wide separations, thus reopening the case for in-situ formation of wide separation gas giants.

### 1.2. *The Role of Disk Dynamics and Morphology in Setting Snowline locations and C/N/O Ratios*

- Disk Composition Regulates Planet Composition. It is thus essential to (1) predict what kinds of planet compositions result from planet location in different parts of the disk, and (2) conversely, back-track planet formation location based on planet composition.
- Disks are complex. Show figure from Henning and Semenov with all processes that occur in disks and discuss which ones I tackle in the thesis.
- However, we do know some things about disks. Volatile molecules have detected in disks (show figure with Spitzer IR spectrum of AA Tauri). Snowlines have also been detected (show CO snowline plot from Qi+13).
- One important signature of atmospheric chemistry is the C/O ratio (explain why and show plot from Molliere+15 which shows the effect of varying C/O ratio on the abundance of other volatiles). Discuss claims that super stellar C/O ratios have been detected (show Wasp 12-b spectrum from Madhusudhan), but have since been refuted. Explain that this poses an intriguing question from a theoretical

standpoint. Mention idea proposed by Oberg+11 (show plot). Discuss that disk dynamics have an important role, which is partly what we tackle in this part of the thesis.

- There are other important volatiles besides H<sub>2</sub>O, CO<sub>2</sub> and CO. Discuss the importance of N<sub>2</sub> and show plot with abundances in comets that show that NH<sub>3</sub> is the main carrier based on observations, but it doesn't account for all the nitrogen in the solar system.
- Ice morphology is important. Discuss why. Discuss how binding energies depend on the ice environment and show plot from Edit's paper.
- It follows that we have to take into account additional volatiles, abundances and ice morphologies

besides disk dynamics to see their effect on snow-line locations and the C/N/O ratios. We tackle this in Chapter xx.

- We demonstrate in this part to the thesis that C/N/O ratios may be used to track a planet's formation origin, when combined with observations, but that more observations are needed.

### 1.3. *Disk-Planet Connection*

Our work in the two main parts of this thesis confirms that there is indeed a tight link between disks and planets. More importantly, as we will demonstrate in detail, the formation and composition of giant planets highly depends on disk location and properties.

This thesis is organized as follows....