Origins of Giant Planet Compositions

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, 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.

Both terrestrial and giant planets are born in protoplanetary disks, which implies that their composition is determined by and tightly linked to the structure and composition of the disk. My research interests therefore lie at the intersection of disk and planetary dynamics and chemistry at the different stages of planet formation, with the ultimate goal of understanding the role of disk volatile chemistry and dynamics in shaping the compositions of nascent planets.

Previous and Current Research

1. Minimum Core Masses for Giant Planet Formation. Gas giants are widely believed to form through core accretion, a theory in which solid protoplanetary cores grow large enough to accumulate a massive atmosphere. Core accretion is particularly challenging in the outer parts of a disk, where long dynamical times make it difficult for a core to grow fast enough before the gas disk dissipates on a timescale of a few million years. At the same time, however, giant planets on wide orbits have been discovered in recent years, which poses the question of how these planets have formed. I addressed this issue by calculating the minimum (critical) core mass M_{crit} required to form a giant planet during the lifetime of the protoplanetary disk – this minimum applies when envelopes accrete around fully formed cores. To obtain robust quantitative results for M_{crit}, I assumed a realistic equation of state (EOS) for the nebular gas and realistic opacities that take into account grain growth. I found that M_{crit} decreases with semimajor axis, from 8 Earth masses (M_E) at 5 AU to 5 M_E at 100 AU. These results are lower than the typically quoted value of 10 M_E and may be up to one order of magnitude lower if grain coagulation is taken into account. Thus my study clearly challenges previous claims that core accretion cannot operate in the outer parts of protoplanetary disks, reopening the case for in situ formation of wide-separation gas giants.

2. Snowlines in Protoplanetary Disks. The locations of volatile snowlines in protoplanetary disks are a defining feature of both gas giant and disk chemistry, as they provide vital information about the abundance of these molecules in gas and dust throughout the disk. In this part of my dissertation, I want to understand the effect of disk dynamical and chemical processes on volatile snowline locations and molecular abundances.

I first focused on the main carbon (C) and oxygen (O) bearing molecules, i.e H_2O, CO_2 and CO. The C/O ratio is an important signature of exoplanet atmosphere and disk chemistry, as small variations of the C/O ratio may affect the abundance of other volatiles by several orders of magnitudes. An important consequence of volatile condensation and sublimation in disks is that disks are expected to present different C/O ratios in the gas and in the icy dust mantles at different disk radii. I explored the effect of radial drift of solids and viscous gas accretion onto the central star on snowline locations. I obtained a powerful result: these two processes alone may move the H_2O, CO_2 and CO snowlines inward by up to 60% compared to a disk in which these effects are not considered. This affects the C/O ratio in gas and dust throughout the disk, and thus has direct implications in shaping the composition of nascent giant planets.

Aside from the main C and O carriers, nitrogen (N) bearing species are important to study. Nitrogen is highly abundant in the Solar system and disks, and primarily found as N_2. Because of the high volatility of N_2, gas phase nitrogen-to-oxygen (N/O) ratio in the outer disk may be even more enhanced than the C/O ratio. Giant planets that form at wide separations should thus have an excess of N in their atmospheres, which could be used to trace their formation origin. By quantifying this effect in disks, I find that the N/O ratio in gas is significantly larger than the Solar abundance, and indeed exceeds the C/O ratio in the outer disk.

Proposed Research

As shown in my work on the minimum core mass of gas giants and snowlines in disks, planet formation depends sensitively on disk physics and chemistry. I propose to develop a holistic chemo-dynamical framework to explore how disk dynamics and chemistry, as well as the dynamics of nascent planets and planetesimals, regulate the compositions of mature giant planets. Such a model will enhance our understanding of planetary structures by enabling us to predict what kind of planet compositions result from planet formation in different parts of the disk. Furthermore, this work provides essential context for characterizing the planets that instruments such as the James Webb Space Telescope (JWST) will one day discover.

1. Coupled Chemical and Dynamical Disk Evolution. Chemical and dynamical processes in a protoplanetary disk affect the disk structure and composition, and thus the composition of nascent planets. Chemical abundances vary significantly across a typical disk, due to steep gradients in temperature, density and radiation. The complexity of disk chemistry means that coupling it with dynamical processes is non-trivial. Through analytical and numerical calculations, I will first explore a range of dynamical processes that may affect the distribution of volatiles in disks, expanding and generalizing the framework I developed during my dissertation research. I will couple this dynamical model with time-dependent chemical models of increasing complexity, informed by results from state-of-the-art disk chemistry models (that can only be run on static disks). This will show how the snowline locations of volatiles, as well as the chemical composition of the disk gas and dust evolve, which has direct implications on the compositions of young planets.

2. Planet and Planetesimal Migration. Giant planets can migrate through the disk while still accumulating gas, which will change their atmospheric composition since the disk chemical abundances are different at different disk locations. Additionally, giant planets may still accumulate planetesimals while accreting nebular gas. The final composition of a planet's atmosphere will thus depend on how much gas and solids are accreted in this stage. I will add planet dynamical effects such as migration and planetesimal accretion in the chemical and dynamical model developed in part 1, and quantify how these processes affect the chemical composition of gas giant envelopes.

3. Model Planet Populations. The results from parts 1 and 2 will feed into a large planet synthesis model, in which I will use a grid of different initial disk and planetary embryo conditions. For this computationally expensive step, I will only include the processes that I have identified to be the most important in the local simulations from steps 1 and 2. This will allow me to constrain a planet's formation location based on its chemical composition. Comparing my results with future JWST observations of atmospheric spectra will lead to great scientific strides in understanding the complex connection between protoplanetary disks and the formation, evolution and composition of exoplanets.

Future Plans

After my tenure as PCEP scholar, I would like to continue pursuing my research in the rich and exciting field that disks and exoplanets provide. One direction in which I see my research going is expanding the framework I will have developed during my postdoctoral work to also incorporate terrestrial planet formation, and therefore their interior and surface compositions. While a planet's solid interior structure cannot be detected, such a study could greatly improve our knowledge of the composition and formation history of currently observed rocky planets. Collaborating with Prof. Leslie Rogers, an expert in both planetary interiors and atmospheres, would therefore be instrumental in achieving my research goals both as a PCEP scholar and beyond. I aspire to become a faculty member and continue my research in the academic environment while sharing my knowledge and expertise with the next generation of astronomers.