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The Role of Water in Planet Formation

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Summary

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Planets form in disks of gas and dust around young stars that are a byproduct of star formation. Most of the gas and dust in these protoplanetary disks is depleted within a few million years, which is a short timescale when compared to the lifetime of stars and planetary systems. The conversion of dust grains to rocky planets and the cores of gas giants must therefore be a relatively fast process. We also know that planet formation is ubiquitous, since thousands of exoplanets — planets revolving around stars other than the Sun — have been discovered in the past decades. On average, every star in the Milky Way has at least one planet. Many of the known exoplanetary systems have architectures that are very different from that of the Solar System. Technologically, it is still difficult to find an identical twin of the Solar System, so the question whether the Earth and the Solar System are unique in a cosmic context, remains unanswered. We do know that exoplanets are highly diverse: several classes of planets that have no counterpart in the Solar System have been discovered, such as 'super-Earths' (rocky planets with masses a few times that of the Earth, typically orbiting at short distances from their host stars), and 'hot Jupiters' (massive gas giants with very short orbital periods).

With the realisation that planets are common and that there is great diversity in exoplanet properties, come questions about planet formation: what physical processes are responsible for converting micron-sized dust grains to planetary embryos within the lifetime of protoplanetary disks? How does the outcome of the planet formation process depend on the disk conditions? What do planet formation theories predict regarding the uniqueness of the Earth? In order to work towards answers to these questions, both observational and theoretical research are necessary. Observationally, the properties of protoplanetary disks can be constrained in several ways, e.g. by measurements of scattered light from the dust grains in the disk surface layers; by observations of (near)-infrared thermal emission of solid particles in the disk midplane; and by detections of emission lines from different gas molecules. Disk observations, and, of course, observations of exoplanet properties, provide valuable constraints to

planet formation theories. However, observations of scattered light and thermal emission from protoplanetary disks are sensitive to relatively small particles of up to a few centimetre, and do not probe larger bodies. Theoretical work is therefore not only needed to interpret the disk and exoplanet observations, but also to fill the observational gap between pebbles and planets. Specifically, the formation of planetesimals (approximately kilometre-sized objects akin to asteroids, which are considered to be an important intermediate step in the planet formation process), and their subsequent growth, is still highly elusive. Also from a theoretical perspective, it is not yet clear exactly how, when, and where planetesimals form. A promising mechanism for planetesimal formation that circumvents the dust growth barriers discussed in chapter 1, is the streaming instability: when the solids-to-gas ratio exceeds a critical value, dense filaments of pebbles emerge as a result of this instability. Clumps of pebbles may subsequently collapse under their own gravity to directly form planetesimals. The requirements for streaming instability; the presence of pebbles (particles that are aerodynamically partly decoupled from the gas disk) and an enhanced solids-to-gas ratio, are an important area of study in planet formation theory.

In this thesis, I have explored the role of water in planet formation with numerical models. Water is the most abundant volatile in protoplanetary disks, and is expected to play an important role in different stages of planet formation. The first part of this thesis is focused on the early stages of planet formation: the growth and dynamics of solid particles and the conditions for the formation of planetesimals by the streaming instability. The attempt to develop a planet formation model that treats the two main stages of planet formation (dust $\rightarrow$ planetesimals and planetesimals $\rightarrow$ planets) self-consistently has culminated in a formation model for the TRAPPIST-1 planetary system.

Planetesimal formation at the water snowline

In chapter 2 we have presented a model of the local region around the water snowline in protoplanetary disks: the distance from the star beyond which water vapour freezes out. Due to the strong dependence of the water evaporation rate on the disk temperature, the density distribution of water vapour exhibits a steep gradient across the snowline region. Turbulent diffusion causes an outward flux of water vapour, which can condense onto pebbles just outside the snowline that are drifting inward due to gas friction. Because inward-drifting icy pebbles are continuously delivering water vapour to the region interior to the snowline, the outward diffusion-condensation effect leads to an enhanced density of solids just outside the snowline. This is important, because a requirement for the formation of planetesimals is a solids density that is enhanced compared to the typical solar metallicity.

We have developed a model in which the time evolution of the surface density distributions of small silicate grains, icy pebbles, and vapour are solved for on a cylin-

drical one-dimensional grid. The model takes into account radial drift (including the back-reaction of dust on the gas), diffusion, gas accretion onto the star, water evaporation and condensation. For a constant gas accretion rate and a constant pebble flux from the outer disk, a steady-state solution is reached. We have quantified the extent to which the solids density outside the snowline gets locally enhanced as a function of different disk parameters. We have focused particularly on the midplane solids-to-gas ratio: if the solids-to-gas ratio at the disk midplane exceeds unity, streaming instability is triggered, leading to dense clumps of pebbles that can subsequently collapse to form planetesimals.

We have presented two variants of the model: one in which we view icy pebbles in the cold outer disk as conglomerates of many tiny (micron-sized) silicate grains that are held together by water ice (the 'many-seeds' model), and one in which icy pebbles consist of a single silicate core with an icy coating (the 'single-seed' model). We found that in the many-seeds model, the solids-to-gas ratio outside the snowline is boosted even more compared to the single-seed scenario. This is because not only water vapour diffuses outward, but the tiny silicate grains do so as well - they are aerodynamically well-coupled to the gas and diffuse outward together with the vapour, after which they stick to the inward-drifting icy pebbles.

We have shown that under plausible disk conditions, the requirements for the streaming instability scenario for planetesimal formation can be reached at an early time in the disk evolution. This promising result has been further exploited in chapter 4 and chapter 5, in which we have employed the semi-analytic model of the snowline presented in chapter 2. The semi-analytic model approximates the numerical results and is computationally very cheap.

Interpretation of the ALMA observation of the water snowline in the V883 Ori disk

Before chapter 4 and chapter 5, however, chapter 3 constitutes an intermezzo in which we turn to an Atacama Large Millimetre/sub-millimetre Array (ALMA) observation of the V883 Ori disk reported by Cieza et al. (2016). V883 Ori is a so-called FU Ori object: a young star that is undergoing an accretion outburst, such that its luminosity has increased by a few orders of magnitude. Due to the increased stellar luminosity, the disk around V883 Ori has been heated and the water snowline has been pushed outward to approximately 40 astronomical units (au) — corresponding to an angular distance resolvable with ALMA. The presence of the water snowline in this disk has been inferred from the radial variation of the spectral index at millimetre wavelengths, which features a steep gradient from low to high values at around 40 au. This has been interpreted as the presence of large icy pebbles outside the water snowline at 40 au and a pile up of small silicate particles interior to 40 au. The pile up of small grains would have been the result of the difference in drift velocities between icy pebbles and

small silicate grains, which leads to a 'traffic jam' of particles interior to the snowline. In this chapter we have shown that the timescale for a 'traffic jam' to materialise is much longer than the outburst timescale, such that a different interpretation is called for. Using the DIANA Opacity Tool to calculate dust opacities at the wavelengths at which ALMA observed the V883 Ori disk, we found that a solids surface density distribution according to our many-seeds model (in which icy pebbles disintegrate into tiny dust grains upon evaporation) can reproduce the ALMA data, if icy pebbles have a low carbon content and if the inner disk was already optically thick before the outburst. We have therefore offered an alternative and more realistic interpretation of the ALMA observation. In order to distinguish our model from a scenario in which the water snowline does not play a role at all in producing a rapid variation in the millimetre spectral index with semi-major axis, more disks around FU Ori objects should be observed.

Global Lagrangian model for dust evolution and planetesimal formation

In chapter 4 we returned to the topic of planetesimal formation. In our local model of the snowline presented in chapter 2, the flux of pebbles arriving at the snowline from the outer disk and the aerodynamic properties of pebbles were input parameters. In chapter 4 we have built a global model, in which we treat the evolution of dust and pebbles and planetesimal formation throughout the entire protoplanetary disk. We have implemented the semi-analytic model of chapter 2 as a 'recipe' to model planetesimal formation outside the snowline due to the water diffusion-condensation effect. Dust evolution is treated in a Lagrangian way: quantities are computed at the locations of super-particles rather than at grid cells as in a Eulerian approach. The surface densities of solids at each super-particle location are calculated using a smoothing kernel. The Lagrangian nature of the model makes it especially suited to following particle characteristics such as water fraction, and our model accounts for the formation of both water-rich and water-poor planetesimals.

We have found that dry planetesimals can form close to the star as a result of fragmentation and pile-up of silicate grains (an effect that was also found by Drążkowska et al. 2016), but that planetesimal formation just outside the snowline is always stronger. We showed that planetesimal formation is self-limiting when pebble accretion is accounted for. With an increasing mass in planetesimals, a larger fraction of the pebble flux arriving from the outer disk gets accreted by the already existing planetesimals, and therefore the fraction of the pebble flux available for formation of new planetesimals becomes smaller. However, in this model we do not yet take into account the dynamical evolution of the planetesimal population; we come back to this in chapter 5. We have applied the model to different stellar masses and found that low-mass stars are more efficient at converting pebbles to planetesimals than high-

mass stars, because the planetesimal formation rate depends inversely on the snowline distance. However, intrinsic variation of disk properties may well overshadow this modest effect.

Formation of the TRAPPIST-1 planets

A particularly interesting exoplanetary system is TRAPPIST-1: a cool M-dwarf star approximately forty light-years away, with seven Earth-sized planets. The planets were discovered with the transit method: they pass in front of their host star as seen from our line of sight, and during these transits, the tiny planet silhouettes on the TRAPPIST-1 star cause observable dips in the stellar brightness. The timings of the transit signals are not exactly regular: the mutual gravitational attraction between the seven planets results in small transit-timing variations, which have been used to constrain the strength of the gravitational attraction and therefore the planet masses. The bulk densities that can be derived from the planet masses and radii are consistent with water contents of a few to tens of mass percent (Grimm et al. 2018; Dorn et al. 2018). The architecture and expected planet water fractions of the TRAPPIST-1 system are puzzling to explain within the classical planetesimal accretion framework. Ormel et al. (2017) have proposed a formation narrative for the TRAPPIST-1 system. In this scenario, planetesimals form outside the snowline (chapter 2) and grow by accreting pebbles. When a protoplanet reaches approximately lunar size, its orbit starts decaying due to gravitational interaction with the gas disk (type-I migration). After a protoplanet has crossed the snowline, the pebbles it can accrete are dry.

In chapter 5 we have performed detailed numerical simulations of this formation scenario for the TRAPPIST-1 planets. We have coupled the dust evolution and planetesimal formation model from chapter 4 with an N-body code that follows the dynamics and growth of planetesimals, accounting for pebble accretion, gas drag and type-I migration (Liu et al. 2019). The final phase of pebble accretion in the very inner disk is calculated with a semi-analytic model to reduce computational cost. The coupling of the three codes enabled us to self-consistently model the assembly of the TRAPPIST-1 planets from small dust grains to full-sized planets. We have shown that planetesimal formation takes place just outside the snowline during a single, early phase in the evolution of the protoplanetary disk, and that multiple Earth-sized planets are a natural outcome, without imposing a pebble isolation mass. We predicted that the water fraction of planets in compact systems such as TRAPPIST-1 shows a 'V-shaped' trend with planet order: from relatively high (innermost planets) to relatively low (middle planets) to relatively high (outer planets). This is because our simulations have shown that the relative contributions of planetary growth mechanisms (wet planetesimal accretion, wet pebble accretion, dry pebble accretion) differ between the inner, middle, and outer planets. The first planets, which end up as the innermost planets, grow predominantly by wet planetesimal accretion. By the time

the middle planets start to grow, the density of planetesimals outside the snowline has decreased, such that dry pebble accretion becomes a more dominant growth mechanism. The planets that end up as the outermost planets have been scattered outward at early times, and have grown predominantly by wet pebble accretion. By the time they arrive at the snowline, the pebble flux has already dried out to such an extent that dry pebble accretion is not that important anymore. The constraints on the bulk densities of the TRAPPIST-1 planets are not yet precise enough to confirm or deny our predicted trend of the water fraction with planet order, but future measurements may provide stronger constraints.

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Samenvatting

De rol van water in planeetvorming

Planeten vormen in schijven van gas en stofdeeltjes rondom jonge sterren, als een bijproduct van stervorming. Verreweg het meeste van het gas en stof in zulke protoplanetaire schijven is na een paar miljoen jaar verdwenen, wat een korte tijdschaal is vergeleken met, bijvoorbeeld, de levensduur van sterren en planetenstelsels. De conversie van stofkorrels naar rotsachtige planeten en de kernen van gasreuzen moet dus een relatief snel proces zijn. Ook weten we dat planeetvorming veelvuldig plaatsvindt, omdat er duizenden exoplaneten — planeten die om een andere ster dan de zon draaien — zijn ontdekt in de afgelopen dertig jaar. Gemiddeld genomen heeft elke ster in de Melkweg een planeet. Veel van de ontdekte exoplanetaire stelsels hebben eigenschappen die erg anders zijn dan die van het zonnestelsel. Technologisch is het nog altijd lastig om een identiek tweelingzusje van de aarde te vinden, dus de vraag of de aarde en het zonnestelsel uniek zijn in een kosmisch perspectief blijft vooralsnog onbeantwoord. Wat we wel weten is dat exoplaneten zeer divers zijn: er zijn meerdere planeetcategorieën ontdekt die we niet kennen uit het zonnestelsel, zoals 'super-aardes' (rotsachtige planeten die een paar keer zo massief zijn als de aarde, en typisch op korte afstanden van hun ster cirkelen), en 'hete Jupiters' (zware gasreuzen die zeer dicht rondom hun ster draaien).

De realisatie dat planeten veel voorkomen en dat er een grote verscheidenheid aan planeeteigenschappen is, leidt tot vragen over planeetvorming: welke fysische processen zijn verantwoordelijk voor de omzetting van kleine stofkorrels in planetaire embryos gedurende de levensduur van een protoplanetaire schijf? Hoe hangt de uitkomst van het planeetvormingsproces af van de condities in de schijf? Wat voorspellen planeetvormingstheorieën over hoe uniek de aarde is? Om dichter tot een antwoord te komen op zulke vragen zijn zowel astronomische waarnemingen als theoretisch onderzoek nodig. Door protoplanetaire schijven te observeren kunnen we op meerdere manieren informatie te weten komen over hun eigenschappen; bijvoorbeeld door afbeeldingen te maken van sterlicht dat verstrooid wordt door stofkorrels in het schijfoppervlak; door het waarnemen van infraroodstraling die wordt uitge-