Mind the gap : gas and dust in planet-forming disks

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Introduction

"We live in a universe whose age we can't quite compute, surrounded by stars whose distances we don't altogether know, filled with matter we can't identify, operating in conformance with physical laws whose properties we don't truly understand." - Bill Bryson: 'A short history of nearly everything'

Since the beginning of humanity, people have looked up to the sky and wondered where they come from. Both religion and philosophy played a major role to explain everything we saw that we could not understand. Observing the motions and phenomena in the sky within the human perspective gives only a limited view on what is going on in the Universe. It is then even harder to imagine that there is a link between the Earth we live on, the Sun that rises and sets every day and the twinkling dots in the night sky. The major question throughout history is the place of humans (and their home planet) within the Universe: from Aristarchos who suggested for the first time that the Sun was the center of the Universe instead of the Earth, to Galileo's discovery of moons orbiting Jupiter, to William Herschel defining the Sun as an ordinary star somewhere in the outer parts of the Milky Way, to exoplanets not quite following the 'perfect' configuration of our Solar System. With time, ideologies and philosophical theories were replaced by science and empirical research. Even now, new discoveries are constantly overtaken by the understanding at that time, creating new problems and challenges for scientists to be solved and new ideas to be explored.

One of the most remarkable revolutions was the idea that stars and planets do not live forever, but that they must be born, live and die. The main trigger for this idea was the discovery of nuclear fusion as the main fuel of stars in the beginning of the 20$^{\text{th}}$ century, which implies directly that there has to be a beginning and end of the fueling process. The Solar Nebular Hypothesis was already proposed in the 18$^{\text{th}}$ century by Emanuel Swedenborg and further developed by Immanuel Kant. This theory contributed to the idea that stars and planets are formed at some stage. It is surprising that the idea of an infinite, unchanging Universe was taken for granted for such a long time, while evidence of birth and death is all around us in every day life. The main reason is again the limitation of the human perspective: the spatial and temporal scales in which things happen in the Universe go beyond our imagination. Even if we put numbers and units to these scales, it is difficult to put a feeling to what it is really like in the Universe. As a consequence, astronomy was for a long time driven by the development of physics itself.

With the technological innovations and the exponential increase of new telescopes and instruments at wavelengths outside the optical regime in the second half of the 20th century, observations did not only confirm or disprove theories, but started to drive new theories. The dawn of every new telescope revealed new objects, new structures, new prospects for our understanding of the Universe. The insight in formation of young stars, disks and planets has been revolutionized by telescopes such as *IRAS*, *Spitzer* and *Herschel* in the infrared, and JCMT, IRAM, APEX and SMA in the (sub)millimeter, where these objects are shining the brightest.

Of particular interest for this thesis are the protoplanetary disks, and the processes leading to the formation of planets in these disks. Disks can be seen as flattened, rotating structures of gas and dust around protostars, which evolve through viscous accretion to gas-poor debris disks. Transition disks, the disks with cleared-out inner dust cavities, are the prime targets of this study. The major questions that we aim to answer in this thesis are the following. What is the structure of the gas in transition disks? What is the clearing mechanism, the origin of dust cavities? How do recently formed planets sculpt their surrounding disk? How can small dust grains grow into larger pebbles and planetesimals, the start of planet formation? What can gas observations tell us about physical processes in disks? In general: what is the role of transition disks in the planet formation process?

The arrival of ALMA, the Atacama Large Millimeter/submillimeter Array, is another revolution in answering these questions. ALMA is an array of 66 antennas operating at (sub)millimeter wavelengths, built at the Chajnantor plateau in the Atacama desert at 5000 m altitude in Chile. ALMA is an international partnership of ESO, NSF (USA) and NINS (Japan), together with NRC (Canada), NSC and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. When finished, the antennas will be equipped with 10 receivers ranging from 30 to 950 GHz (0.3 millimeter up to 1 cm) and placed in configurations with baselines up to 16 kilometer, resulting in spatial resolutions at the mas level. Both the sensitivity and spatial resolution exceed the pioneering millimeter interferometers by two orders of magnitude. Of particular importance for this thesis are the high frequency Band 9 receivers operating at 690 GHz (Baryshev et al. 2015), developed by NOVA (the Netherlands Research School for Astronomy) and SRON (Netherlands Institute for Space Research). ALMA started operations in 2011 with a partially completed array of 16 antennas and 4 receivers with baselines up to 400 meter (0.2" resolution at the highest frequency) and has gradually increased its capacities in the following years. ALMA allows us to zoom in deeper on the birth of planets than any other telescope before, unraveling more questions than we could ever have imagined in the wonder about our origin.

1.1 Stars, disks and planets

1.1.1 Star formation

Stars and planets are ubiquitous in the universe and their formation process has been the subject of decades of study (see reviews e.g. Shu et al. 1987; Williams & Cieza 2011; Armitage 2011; André et al. 2014; Raymond et al. 2014; Helled et al. 2014). Planets are thought to form in protoplanetary disks of gas and dust around young low-mass and intermediate mass (<8 $M_\odot$) protostars (see Figure 1.1 for an evolutionary sequence). These disks are a natural consequence of star formation. A star is formed by gravitational collapse of a molecular cloud, where the conservation of angular momentum ensures the spin up of material leading to a flattened, rotating structure around the star, called a *'disk'*. The cloud mass is dominated by the gas with a typical gas-to-dust ratio of 100. In the early phases of evolution the disk is surrounded and fed by the protostellar envelope (*embedded disk*) and simultaneously depositing material onto the still forming star for a period of a few 10^5 years (Evans et al. 2009; Dunham et al. 2014). After this, a period of several Myr years starts in which the disk disperses its material, through viscous accretion inside the disk and stellar winds at the disk surface. Since the bulk of the disk mass is in the gas, the gas dominates the dynamical processes in the disk. By some critical point, the disk has lost a large fraction of its gas mass and accretion onto the star has come to an end. Some, if not all planets in the system may already have formed at this stage. The star continues its evolutionary path towards the main sequence until hydrogen fusion starts; by this time the star and its surrounding planets have several billion relaxing years ahead of them until the star has run out of its nuclear fuel. Although the formation of high-mass stars (>8 $M_\odot$) likely follows more or less the same sequence of events, the physical processes behind it are less well understood due to the destructive consequences of their much higher radiation fields.

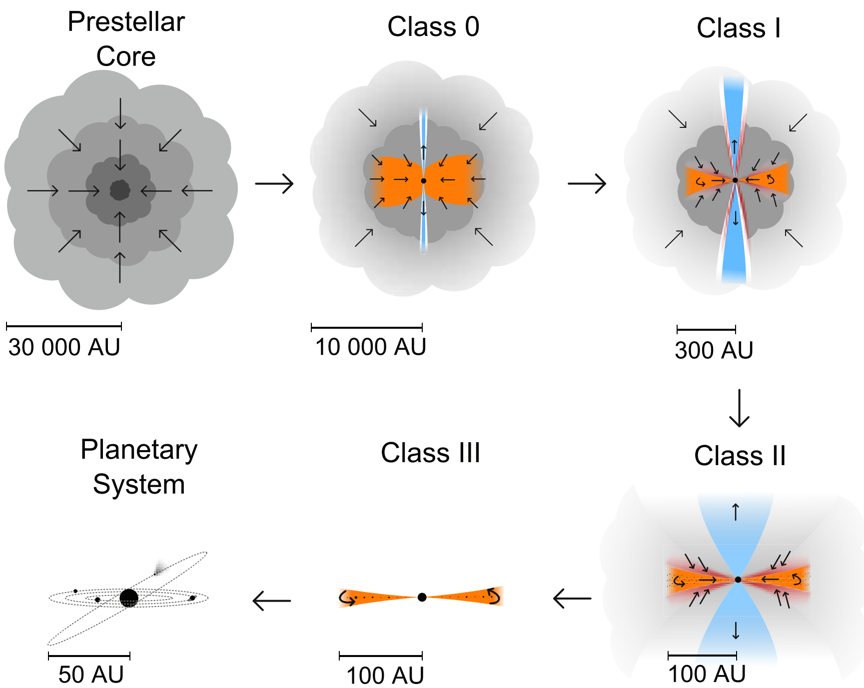

Figure 1.1: *The evolutionary process of star and planet formation. A prestellar core collapses to a protostar still embedded in its envelope. Material keeps falling in and a rotating disk forms around the star. Molecular outflows and accretion remove the envelope material, until only a disk remains. The disk evolves from a massive gas-rich to a gas-poor debris disk, ending as a planetary system. Figure by Magnus Persson.*

1.1.2 Planet formation

One of the many open questions is when and how the formation of planets fit into this story. Current statistical studies of exoplanets suggest that most stars in the Milky Way (and perhaps the Universe) hosts at least one planet (Batalha 2014). This conclusion raises the question whether planets are just a natural by-product of disk evolution and star formation. Since the construction of a planet is a long-lasting process taking up millions of years (see Section 1.2), we have to study the structure of their birth cradles, the protoplanetary disks, in order to learn more about the relevant physical processes. This thesis focuses on the structure of the gas and dust in disks, which is now possible due to the sensitivity and spatial resolution of ALMA, which started operations only a few years ago. Interestingly, the Solar Nebular Hypothesis was proposed long before astronomers could prove the presence of circumstellar disks around other stars and study how planets form inside these disks.

1.1.3 Protoplanetary disks

The objects that are now known as young stars with circumstellar disks were originally identified through optical observations as pre-main sequence stars that were thought to be in the middle of their formation; the presence of disks was not confirmed until several decades later. The main characteristics of this new class of stars pointing to their pre-main sequence status were e.g. their systematically higher brightness compared to main sequence stars of the same spectral type; their overabundance inside dark clouds; and strong optical emission lines such as the hydrogen Balmer lines (e.g. Hα) and Ca II (Joy 1945; Herbig 1957). They were called T Tauri stars and their massive, bright equivalents the Herbig Ae/Be stars. The latter were recognized early on as equivalent to T Tauri stars (Herbig 1960), with the distinct difference that the star is of earlier type and illuminates a reflection nebula, which is a natural consequence of the star being brighter.

Initially the T Tauri/Herbig stars were thus not even known to have disks. T Tauri stars often show emission excess in the UV with respect to the stellar photosphere, which is not so evident in Herbig stars. At this stage, two types of T Tauri stars were known: *classical* (CTTS) and *weak-line* (WTTS or NTTS: naked TTS), referring to the emission strength and width of the Hα line. In addition WTTS show strong X-ray emission (e.g. Walter & Kuhi 1981) and much less UV excess. The first evidence for dust grains surrounding these stars was found through additional emission excess above the photosphere in the infrared up to 5 μm (Mendoza V. 1966). However, the pieces of the puzzle were not put together until the suggestion of a self-luminous viscous accretion disk model to explain the nature of both of these types of excess emission (Lynden-Bell & Pringle 1974; Kenyon & Hartmann 1987). This was also the time that both UV and far infrared data became available through the *International Ultraviolet Explorer (IUE)* and the *InfraRed Astronomical Satellite (IRAS)* in 1978 and 1983, respectively. The bright infrared emission with optically visible stars proved that the dust grains could not be distributed in a spherical shell, as this would result in much higher optical extinction. Therefore the emission had to originate from a physically thin structure: a disk. Another piece of evidence for disks was found through optical spectroscopy showing only the blue-shifted component of forbidden line emission: the red-shifted emission is obscured by an occulting disk (e.g. Edwards et al. 1987; Bertout 1989). The recognition and understanding of disks has thus always been strongly driven by new observational facilities, just as this thesis is largely driven by ALMA.

Remarkably, one of the main reasons that T Tauri and Herbig stars were even recognized as a signature of protostellar evolution, is their similarity to high mass counterparts seen in short-lived (and thus recently formed) OB associations, whereas the high-mass star formation process itself remains much less understood. The Herbig stars were studied largely separately from T Tauri stars due to their bright nature and thus easy observability. This terminology splits up the pre-main sequence stars in different categories, whereas they are likely just similar in nature, albeit with a different spectral type and mass, and thus a different evolutionary pace. In this thesis we study several disks for a range of spectral types from A-type Herbig to M-type T Tauri stars.

In the decades after the discovery of circumstellar disks through excess emission, they were successfully imaged: the nearby β Pic debris disk in scattered light (Smith & Terrile 1984), the ‘proplyds’ (acronym for protoplanetary disks seen in silhouette against a bright HII region) in Orion with the *Hubble Space Telescope* (O'Dell et al. 1993) and the millimeter continuum and CO line images showing Keplerian rotation (e.g. Sargent & Beckwith 1987). Accretion was related to UV excess and optical line emission (Kenyon & Hartmann 1987). With the availability of infrared data from *IRAS* and *Infrared Space Observatory (ISO)* an evolutionary sequence in the path of planet formation was proposed (Adams et al. 1987): from the disks deeply embedded in their envelope (Class I), to the young stars with a bright accreting disk (Class II or CTTS), to the pre-main sequence stars with only weak disk and accretion signatures (Class III or WTTS).

This classification (Lada classification) relies on the infrared part of the Spectral Energy Distribution or SED: the (spatially unresolved) photometric spectrum from optical to millimeter wavelengths. Dust grains are heated by the star and by viscous heating, and emit primarily through thermal emission. As the dust temperature in a disk (or envelope) largely depends on the distance from the central heating source, this results in a broad continuous excess above the stellar photosphere at infrared and longer wavelengths due to the range of temperature in the disk. Disk emission is clearly distinct from envelope emission because a spherical envelope obscures a much larger fraction of the emission originating from the protostar. With the *Spitzer Space Telescope* complete samples of young stellar objects in nearby star-forming regions were constructed. From the complete survey of star-forming regions it was possible to compute statistics and derive typical time scales of the different stages in the star and disk evolution process, which were compared to evolutionary models (e.g. Evans et al. 2009). Disks around young stars were found to be a common feature. At the same time the number of discovered exoplanets was steadily growing, giving more and more evidence that planets around stars are ubiquitous.

1.1.4 Transition disks

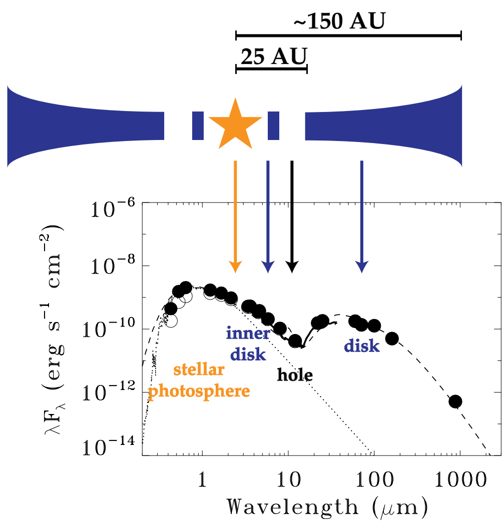

Figure 1.2: *Spectral Energy Distribution of a transition disk, showing the different components of the system and their emitting wavelengths. The stellar photosphere emits as a blackbody in optical to near-infrared wavelengths, an inner disk is recognized as near-infrared excess above the photosphere due to hot dust grains, the hole is seen as a dip in the mid-infrared, while the bulk of the dust in the outer disk emits in far-infrared up to millimeter wavelengths.*

One of the main questions in this evolutionary process is the transformation of the massive, gas-rich circumstellar Class II disks towards the tenuous Class III debris disks with planets. During this crucial transition the material from the disk is accreted onto the star, dispersed into the interstellar medium and possibly merged into planets, although planet formation could also start at an earlier stage. The transition is thought to be rapid, due to the small amount of disks with properties in between Class II and III (or between CTTS and WTTS). The discovery of disks with a dip in the mid infrared excess in the SED through *IRAS* photometry was interpreted as a sign of inner holes or dust clearing (Strom et al. 1989). This group of disks were named 'transition disks' (see Figure 1.2), although it remains unclear whether all disks go through a 'transition disk phase'. Several other disks with cleared inner cavities were identified 10-15 years later through dips in their Spitzer IRS spectra (5-35 μm) (Forrest et al. 2004; Calvet et al. 2005; Brown et al. 2007).

In this transitional phase a range of processes were thought to be responsible for the appearance of a cavity (see also next section): (1) grain growth, where dust grains inside the cavity have grown to larger sizes that do not emit sufficiently at the observed wavelength; (2) photoevaporative clearing, where the stellar UV heats gas to temperatures above the escape speed, resulting in a photoevaporative wind that clears the disk from the inside out; (3) certain instabilities leading to dust concentrations in the outer disk; (4) companion clearing, where either a planet or a star carves a gap in the dust and gas in their orbit.

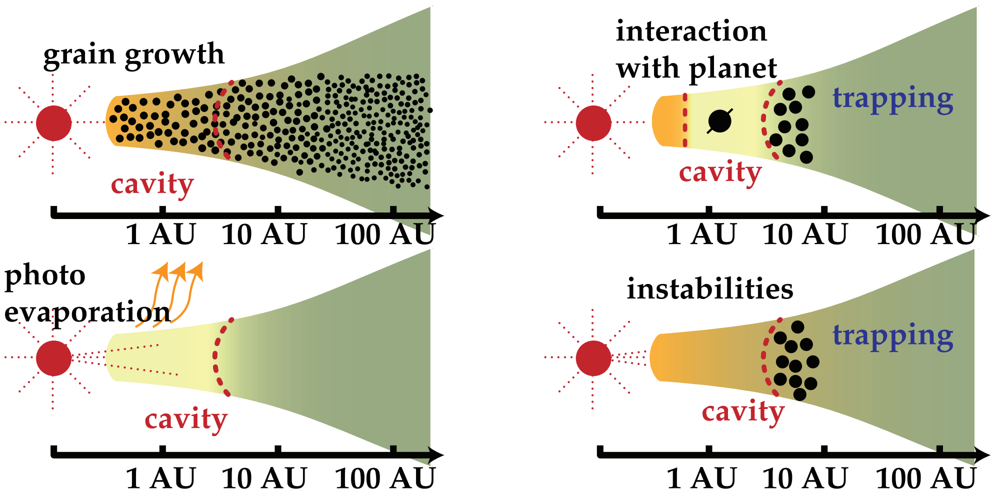

Figure 1.3: *Cavity clearing mechanisms in dust (black dots) and gas (yellow).* **Top left:** *increased grain growth inside the cavity, while the gas density remains unchanged compared with the original disk.* **Bottom left:** *photoevaporative clearing, with both the gas and dust cleared simultaneously from the inside out.* **Top right:** *clearing by a companion, in which the gas density inside the cavity drops and the large dust particles get trapped at the edge.* **Bottom right:** *instabilities due to e.g. viscosity or entropy gradients create a dust trap, the gas density remains unchanged. Figure based on cartoon by Simon Bruderer.*

The discovery of transition disks thus opened up an interesting possibility of studying the most important disk evolution processes for understanding planet formation. Most observational studies of transition disks have focused on the dust distribution in these disks, while the key for distinguishing between the mechanisms lies in the gas, which is predicted to be different in all cases (see Figure 1.3): the gas density is unaffected by grain growth and certain instabilities, is cleared completely by photoevaporation from the inside out and is reduced in case of companion clearing depending on the companion mass and disk viscosity (Lubow & D'Angelo 2006; Crida et al. 2006; Pinilla et al. 2012a).

Early observations have revealed evidence for the presence of warm atomic and molecular gas inside dust cavities from optical and infrared observations (e.g. Najita et al. 2003; Acke & van den Ancker 2004; Salyk et al. 2007; Pontoppidan et al. 2008). However, measurements of the bulk of the molecular material inside the dust cavity was not possible until the arrival of ALMA. In this thesis we quantify the gas distribution directly with resolved ALMA observations of several transition disks in order to answer the questions of their underlying clearing mechanism and their role in planet formation and disk evolution.

1.2 Disk processes

With a large range of observations of the planet birth cradles, the step towards solving the puzzle of planet formation itself appears to be close, but this could not be further from reality: although increasingly sophisticated evolution models explain a large range of disk properties and physical processes, planet formation itself remains a mystery, as any theory that has been developed so far ultimately breaks down when compared to the actual time scales and exoplanet properties. Transition disks are promising candidates with active planet formation. The spatially resolved ALMA observations of gas and dust presented in this thesis can be compared directly with physical disk processes to get a better understanding of their role in disk evolution.

1.2.1 Dust evolution

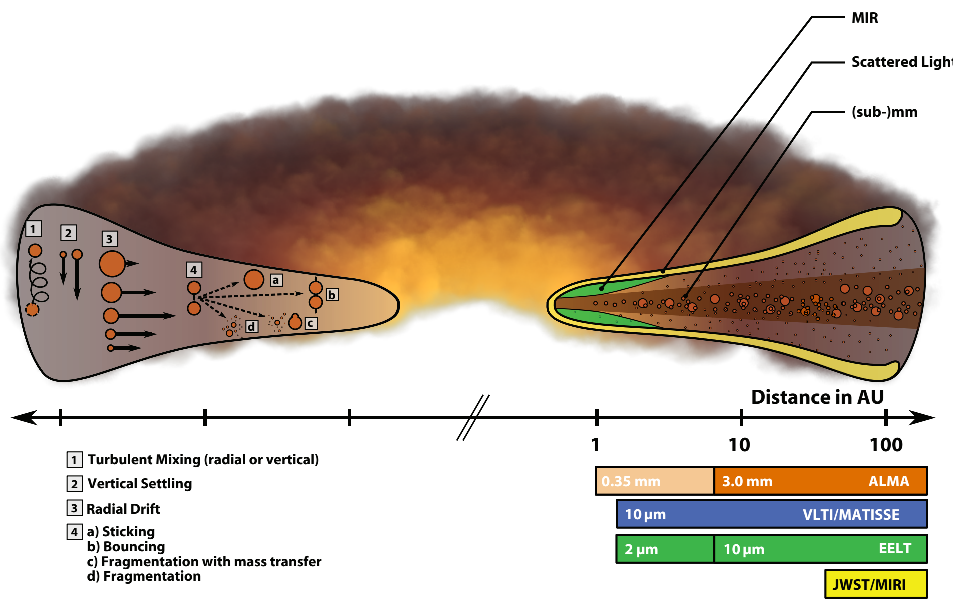

Figure 1.4: *Dust processes in the disk. The left part shows the physical processes affecting the dust grains in the disk, as described in the text. The right part shows which section of the disk is observed at different wavelengths, as discussed in Section 2.3. Figure taken from Testi et al. (2014).*

The starting point of planet formation lies in the evolution of dust grains: the growth of small (sub)micron-sized particles, which are present in the interstellar medium (ISM), to centimeter-sized pebbles, planetesimals and beyond. Several physical processes are involved in grain growth in disks, which need to be taken into account in models. Dust grains can grow by collisions, followed by either coagulation or fragmentation, depending on the relative velocities (which in turn are affected by turbulence, drift, mixing and location in the disk) and the grain stickiness (composition, icy layers and fluffiness or shape). Dust evolution requires numerical modeling, with constraints on the collision outcomes set by laboratory experiments (Blum & Wurm 2008). Dust growth models show that ISM grains can indeed efficiently grow to millimeter sizes within 10^5 year time scales (Brauer et al. 2008). However, growth is stymied by several processes, including fragmentation and drift.

The most important issue is the presence of gas in the disk, which prevents dust particles from moving freely: they experience a drag force (depending on their physical size) when they move relative to the gas. One of the consequences is vertical settling: larger dust particles settle to the midplane of the disk due to damping of the drag force, although turbulent mixing partially opposes the effect. The vertical structure of dust particles is thus an equilibrium between settling and mixing (e.g. Dullemond & Dominik 2004). Another consequence is the *radial drift problem* (Whipple 1972; Weidenschilling 1977). Dust and gas orbit in Keplerian motion in a protoplanetary disk, due to gravitational and centrifugal forces. However, the gas feels an additional pressure force, due to the outward pointing pressure gradient in the disk, resulting in slightly sub-Keplerian velocities of the gas. This causes a head-wind or friction for the dust particles, which consequently lose angular momentum and spiral inwards on short time scales: typically 100 years for a one-meter-sized object at 1 AU or a millimeter-sized dust grain at 100 AU, since the efficiency of this phenomenon depends on the dust particle size and orbital time scale. This 'meter-size-barrier' prevents particles to grow to larger pebbles, which is a crucial first step in planet formation. Radial drift also predicts that larger grains are radially more concentrated than the gas in a protoplanetary disk.

If the drift barrier can be overcome, the fragmentation barrier limits dust to grow beyond 1 meter in the outer disk. Fragmentation occurs when larger particles collide with relatively high velocities (Brauer et al. 2008). In principle this problem can be overcome when additional dust growth mechanisms such as sweep-up and mass transfer are included (Xie et al. 2010; Windmark et al. 2012). However, the radial drift problem can not be solved by dust processes alone.

1.2.2 Disk dynamics and dust trapping

A possible way to overcome the radial drift problem is to trap dust particles in so-called *pressure bumps* in the gas. A local region of high pressure in the outer disk provides a negative pressure gradient outwards, reversing the drift direction and effectively trapping the dust particles (Whipple 1972). Anti-cyclonic vortices in disks were suggested first to act as pressure bumps (Barge & Sommeria 1995; Klahr & Henning 1997).

Vortices result from hydrodynamical processes such as Rossby-wave and baroclinic instabilities in a disk (Lovelace et al. 1999; Klahr & Bodenheimer 2003). Several other physical processes in a disk can create dust traps: the most well-known are the density bumps at the edges of gaps cleared by planets (Zhu et al. 2011; Pinilla et al. 2012a, and Figure 1.5) and the edges of so-called dead zones. Dead zones are regions of low ionization in the disk in which the MRI angular momentum transport does not work (MRI is magnetorotational instability). They can form spontaneously in between cosmic or UV-ray ionized low-density outer regions and collisionally ionized warm high-density inner regions of disks (Varnière & Tagger 2006; Regály et al. 2012). These and other processes are described in more detail in Armitage (2011). The planet-gap scenario is interesting as it returns to the original question of what causes the clearing of a transition disk. However, as an explanation of the planet formation scenario it creates a chicken and egg problem: if a dust trap is required to grow particles and form planets, where does the first planet that has made the dust trap come from?

1.2.3 Planetesimal and planet formation

In general, a radial pressure trap would result in a ring of millimeter-sized particles, while an azimuthal maximum such as seen in a vortex would result in an asymmetric millimeter-dust distribution (Wolf & Klahr 2002; Regály et al. 2012; Birnstiel et al. 2013). In this thesis we present the first clear observational evidence for such a dust trap in the Oph IRS 48 disk. Other transition disks imaged by ALMA show asymmetric dust distributions (Casassus et al. 2013; Pérez et al. 2014). Trapping depends on the particle size, so smaller particles are predicted to spread further throughout the disk and continue to flow inwards through the gap. This radial segregation of small vs large particles is also referred to as dust filtration (Rice et al. 2006). On the other hand, larger centimeter-sized dust particles are expected to be even further concentrated in a dust trap, either radially or azimuthally. This is indeed found for the dust trap in IRS 48 as well.

Time-dependent dust evolution models show that dust not only gets trapped but also grows more efficiently inside these traps, as fragmentation is lower due to a decrease in relative velocities (Brauer et al. 2008). Growth continues up to planetesimal sizes, which can then grow further to rocky planets through runaway or orderly growth, as their own gravitational field starts to attract planetesimals in their surroundings. Once a rocky planet of >10 Earth masses has been formed, the *core accretion* model predicts the formation of a gas giant, where the planet accretes gas from the disk. This implies that the rocky core needs to be formed before the gas disk has dissipated. Alternatively *gravitational instability* can result in disk fragmentation and quick gas giant formation (e.g. Helled et al. 2014). Both models have difficulties explaining the observed exoplanets and their orbital radii, also due to the expected migration of planets through the disk-planet torques.

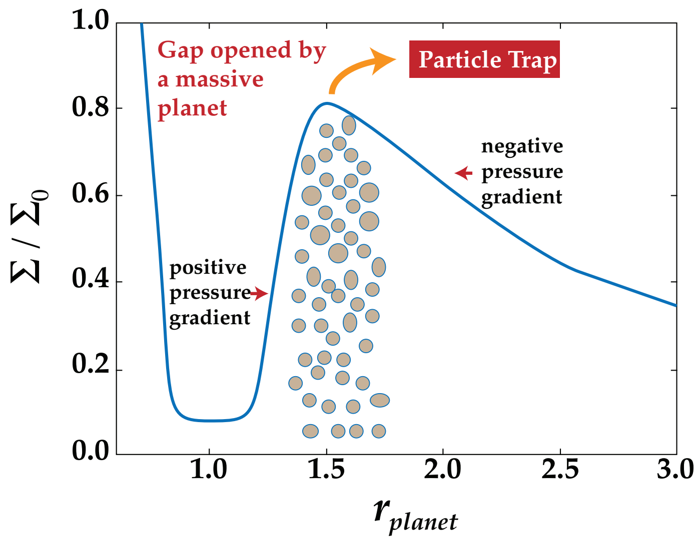

Figure 1.5: *Cartoon of a radial pressure bump, induced by a planet. The gas surface density is lowered at the location of the planet, resulting in a pressure maximum at the edge of the gap, where the milimeter dust gets trapped. Figure by Paola Pinilla.*

1.2.4 Disk dispersion and photoevaporation

Although planet formation is one of the major drivers for disk studies, it is not the main reason why disks disappear: observations of both the Solar System and exoplanets show that planets contain only $\lesssim$1% of the initial disk mass. Instead, the main mechanisms for disk dissipation are accretion onto the star and photoevaporation (Hollenbach et al. 2000; Gorti et al. 2009; Alexander et al. 2014): stellar and interstellar high energy radiation (UV and/or X-rays) heats the disk surface to higher temperatures, up to the point where the thermal energy exceeds the gravitational binding energy and the heated gas escapes as a photoevaporative wind. Disk dispersal by photoevaporation becomes important when the accretion rate from the disk onto the star drops below the photoevaporation rate: at that point the material in the inner part of the disk is no longer replenished by the outer disk and will disappear from the inside out on time scales of $\sim 10^5$ years. Transition disks with cleared out cavities have been suggested to be caused by photoevaporation, but disks with large cavities (R >20 AU) which are still strongly accreting cannot be explained by photoevaporation models only (Owen & Clarke 2012).

1.3 Observations

Disk theories are developed from a theoretical point of view, in attempts to explain planet formation, and directly driven by disk observations. New observations provide better constraints but also raise new questions: the measurement of millimeter fluxes in disks confirmed larger particles in disks than in the ISM (Beckwith & Sargent 1991) but set the challenge of solving the radial drift problem; the discovery of the stellar companion of CoKu Tau 4 solved the question of its large cavity (Ireland & Kraus 2008) but binarity could not explain other transition disks; scattered light imaging confirmed a gap in the small dust grains in some disks but did not reveal a cavity in others (e.g. Follette et al. 2013); large cavity sizes were confirmed by millimeter interferometry observations (Andrews et al. 2011), but they were generally too large to match with exoplanet orbital radii (planet clearing mechanism) or photoevaporation models. This thesis combines the results of several of the studies mentioned above with new ALMA data and resolves some of the issues.

1.3.1 SEDs

One of the difficulties of disk observations is their low mass (only a fraction of the cloud mass) and thus total flux and their angular size: due to the distances of the nearby star-forming regions of ~100-200 pc, disks are typically only a few arcseconds in size. Their detection and identification was relatively easy when the first infrared observations became available through *IRAS* photometry in the 1980s. However, resolving disks was only possible for the proplyds in silhouette against a bright background until the arrival of the first millimeter interferometers in the early 2000s. Fortunately, even SEDs consisting of unresolved photometry fluxes provide important information on the structure of the dust disk, especially transition disks. As the dip in the mid infrared part of the SED is the main signature of a transition disk, the *Spitzer Space Telescope* with a wavelength range from 3.6 up to 70 μm was by far the most important tool to recognize and study transition disks. All nearby star forming regions were observed in the Cores to Disks (c2d) and Gould Belt *Spitzer* programs, and several transition disks were discovered by observations with the *Spitzer* IRS spectrograph 5-35 μm range.

Disk structure in the SED The SED of a transition disk consists of signatures of the stellar photosphere in the optical/near-infared, accretion in the UV, the presence of an inner dust disk in the near-infrared and the outer dust disk at wavelengths from mid-infrared up to millimeter emission (Figure 1.2). The continuum emission at long wavelengths probes the cold, optically thin millimeter-sized dust. Some disks have a strong near-infrared excess while others do not, implying systems with and without an optically thick inner disk. Espaillat et al. (2007) interpret the existence of these two types of systems as an evolutionary effect and name them pre-transitional and transitional, respectively, as clearing by a companion would first just clear a gap and later remove the inner disk entirely. However, as the clearing mechanism is unknown for most disks and as material needs to continue to flow through the gap to explain the accretion onto the star, one needs to be careful with interpreting this observational difference as a real evolutionary sequence. Hence the term pre-transitional disk will not be used in this work.

Identifying transition disks A transition disk is often identified in the SED by comparison with a representative disk (usually the median SED of disks in the well-studied Taurus star forming region): typically the excess between 5 and 20 μm is lower in a transition disk while the SEDs are similar at longer wavelengths. A problem of photometry is confusion: the large beam size of *IRAS* could contain multiple young stellar objects, as they are often grouped together, leading to overestimating the excess emission and the false presence of a mid-infrared deficit. The *Spitzer* beam was better at the longest wavelengths where the beam is largest, with a 70 μm beam size of 15", similar to single dish submillimeter observations. Photometry of the *Herschel* telescope with a 4 times larger mirror has revealed cases of *Spitzer* confusion of objects at 70 μm (Ribas et al. 2013).

With the large surveys from *Spitzer*, several criteria of infrared colors have been developed in order to select transition disk candidates from surveys, which have been tested against sources with full IRS spectra available (e.g. Brown et al. 2007; Hernández et al. 2007; Cieza et al. 2010; Merín et al. 2010). In this thesis we present a study of a large transition disk candidate sample, using color criteria on the *Spitzer* catalogs.

Modeling transition disks For a proper assessment of the disk structure and its cavity, SED modeling with a radiative transfer code is required, such as RADMC, MCFOST and McMAX (Dullemond & Dominik 2004; Pinte et al. 2006; Min et al. 2009). These codes calculate the expected dust emission based on a given 2D density structure by computing the dust temperature at all locations in the disk from the scattering and absorption of photons from a central star. The density structure of a transition disk is usually assumed to be a radially decreasing surface density law with a sharp cavity in the inner part of the disk and, if required by near-infrared excess, an inner disk close to the star (see Figure 1.6). The vertical structure (flaring or settling) is either calculated from hydrostatic equilibrium or parametrized. The vertical structure is particularly important. A flaring disk intercepts more radiation in the outer part of the disk, while a high scale height in the inner disk and at the wall edge can cast a shadow on the outer disk, lowering the temperature and thus the emission at far-infrared and longer wavelengths. Dust opacities are a key ingredient for any radiative transfer model and require assumptions about the dust composition and grain size distribution. Silicate and polyaromatic hydrocarbon (PAH) features that are sometimes seen in the mid-infrared spectrum set constraints on the dust composition (e.g. Kessler-Silacci et al. 2006). Transition disks have been successfully fit with SED modeling, in particular those SEDs for which IRS spectra with fluxes between 5-35 μm were available (Brown et al. 2007; Merín et al. 2010). Using millimeter interferometry (see Section 1.3.3), dust cavity sizes were confirmed to be within a factor of two of the results from SED modeling (Brown et al. 2009; Andrews et al. 2011). Degeneracies in SED modeling exist, especially in the vertical structure and amount

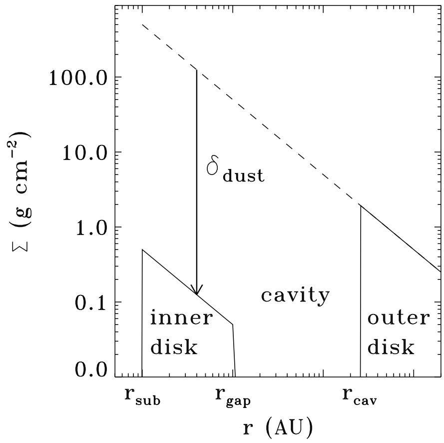

Figure 1.6: *Typical dust density structure for modeling a transition disk.*

of dust in the inner disk, which influence the derived cavity size.

Time domain studies of SEDs have shown so-called ‘seesaw’ variability in some transition disks where the slope of the infrared spectrum changes with time on time scales of weeks up to years. This suggests changes in the inner disk structure with time although it remains unclear what causes this behaviour (Muzerolle et al. 2009; Espaillat et al. 2011).

1.3.2 Gas observations

Whereas the dust distribution in disks has been studied to great detail, observational constraints on the gas distribution are rather limited, while the gas is considered to be dominating the disk properties such as mass and dynamical processes. In particular, the clearing mechanisms for transition disks described above have similar effects on the dust distribution, while the gas is affected in completely different ways and provides thus a way to distinguish between them (see Figure 1.3). Photoevaporation removes the gas and dust simultaneously, a companion would lower the gas density and trap the millimeter-sized dust at the edge and instabilities (and grain growth) would not significantly change the gas density inside the cavity at all. In particular, in case of a companion, planet-disk interaction models have shown that knowing the depth and shape of the gas gap could set constraints on the disk viscosity and planet mass (Crida et al. 2006; Pinilla et al. 2012a). Measuring the gas density inside and outside the dust cavity is thus a crucial step in understanding the transition disks, which is the main topic of this thesis.

Molecular line observations The reasons for the limited amount of gas observations to date are the low line sensitivity compared to continuum sensitivity for most instruments, confusion with surrounding envelope material (for single dish observations) and lack of direct density tracers. While the bulk of the gas mass is in H_2, its molecular lines cannot be used as mass tracer due to its lack of dipole moment. CO (with its isotopologues ^{13}CO and C^{18}O) is the second most abundant molecule in the gas and has been detected in several disks (e.g. Dutrey et al. 1997; Dent et al. 2005). The proper interpretation of CO as column density tracer is challenging. CO rotational emission cannot be translated directly into mass for several reasons. First, the ^{12}CO and ^{13}CO lines are usually optically thick. Second, the gas temperature is decoupled from the dust temperature, especially in the higher layers in the disk. Third, the CO abundance is not constant with respect to H_2: in the surface layers CO is photodissociated by stellar radiation; in the mid-plane the CO freezes out onto the dust grains due to the low temperatures; and the chemical formation/destruction of CO depends strongly on the local density, temperature and radiation conditions (van Zadelhoff et al. 2001; Woitke et al. 2009). Even though the gas motion is Keplerian, the line-of-sight velocity is confused by contributions from different parts of the disk and it is almost impossible to derive mass information from unresolved spectra alone. Spatially resolved observations in combination with a physical-chemical modeling tool for proper interpretation of the emission are thus required for study of the gas density distribution.

The physical-chemical modeling tool developed for the purpose of interpreting molecular line emission in disks and in particular transition disks in this thesis is DALI (Dust And LInes) (Bruderer et al. 2012; Bruderer 2013). The DALI code first solves the dust radiative transfer in 2D for a given density structure and stellar radiation field. With the derived dust temperatures as starting point, the heating-cooling balance of the gas and chemistry are solved simultaneously to determine the gas temperature, molecular abundances and molecular excitation. All effects discussed above are thus taken into account. Special attention is paid to the chemistry and heating inside the dust-free cavities (Jonkheid et al. 2006). The resulting CO abundance in the disk in combination with the gas temperature determine the intensity and profile of the CO line emission in the final step, the ray tracer. The code is summarized in Figure 1.7. For CO isotopologues it was shown that isotope-selective photodissociation plays an important role: without the inclusion of this effect the column density based on $C^{18}O$ observations can be severely underestimated (Miotello et al. 2014). In this thesis we have used DALI to analyze the gas structure in several transition disks.

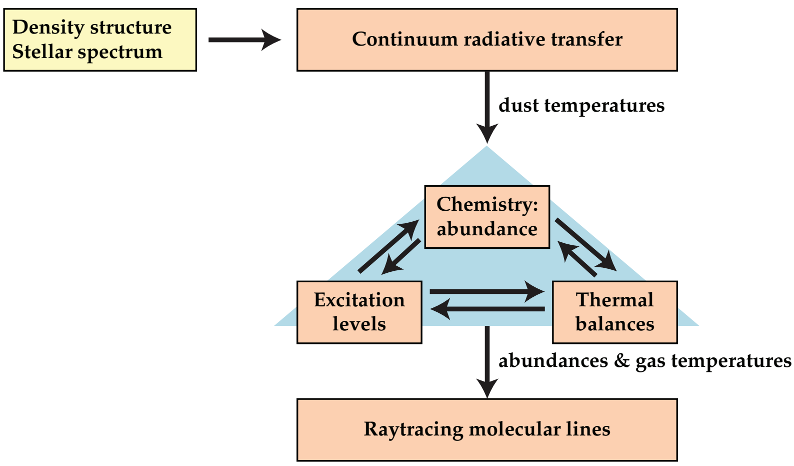

Figure 1.7: *DALI modeling structure. The input of the model is a 2D density structure and a stellar spectrum. Using dust radiative transfer (based on RADMC), the dust temperatures are calculated. DALI then solves the heating-cooling balance of the gas to determine molecular abundances, temperatures and excitation before raytracing spectra and spectral line cubes.*

A similar modeling code is ProDiMo (Protoplanetary Disk Modeling), which was developed to interpret infrared lines observed with Herschel (Woitke et al. 2009), and has a comparable approach as DALI. Other codes to interpret gas line emission are e.g. ANDES (Akimkin et al. 2013) and the code developed by Gorti & Hollenbach (2004).

Gas inside the cavity The presence of accretion in the majority of the transition disks suggests that some gas must still be present inside the dust cavities. This gas is hotter than in the outer disk and can be traced by ro-vibrational and atomic lines, which can reveal the presence and kinematics of molecules, but no global density information. Ro-vibrational CO line observations at 4.7μm of several bright transition disks reveal Keplerian gas down to radii smaller than the dust cavity radius using the spectroastrometry technique for e.g. Oph IRS 48, SR 21 and HD135344B (Pontoppidan et al. 2008; Brown et al. 2012a), which are key targets in this thesis. For other disks, the CO line observations are often single-peaked, consistent with a photoevaporative wind (Bast et al. 2011; Brown et al. 2013), previously seen in [Ne II] line emission (Pascucci et al. 2007; Lahuis et al. 2007). However, although these results are promising, they do not indisputably reveal the gas surface density structure and thus the mechanism responsible for the transition disk. The ALMA observations presented in this thesis reveal deep drops in the gas density inside the dust cavity, where the gas cavity is smaller than the dust cavity, hinting directly at the presence of embedded planets. The proper interpretation was possible due to the use of the DALI model.

Disk chemistry The chemical composition of planet atmospheres is related to the chemical composition of the disk. Emission originating from the outer disk from simple molecules such as HCO^+, CS, HCN, CN, H_2CO, N_2H^+ and H_2O have been detected in several disks in rotational line emission (Dutrey et al. 1997; Thi et al. 2004; Dent et al. 2005; Öberg et al. 2011; Hogerheijde et al. 2011, e.g.). Herschel observations reveal the presence of high J H_2O, CO, [O I], OH, CH^+ and [C II] lines originating from the hot surface layers of the disk (Meeus et al. 2012; Fedele et al. 2013). An interesting aspect is that the chemical complexity is observed to be higher for T Tauri stars compared to Herbig stars despite their lower stellar brightness: the larger FUV luminosities of the Herbig stars leads to more efficient photodissociation of molecules. Complex organic molecules in disks form the building blocks of life on planets. However, the chemical variation in disks detected to date is rather low: apart from the simple molecules mentioned above, slightly more complex molecules c-C_3H_2 (Qi et al. 2013a) and CH_3CN (Öberg et al. 2015) have only recently been detected in transition disks by ALMA. This is surprising, as the presence of a cavity allows a view into the normally hidden midplane composition. Many complex molecules are expected to be formed and locked up in ices in a disk, but the directly UV irradiated wall in a transition disk should result in increased photodesorption of these ices (Cleeves et al. 2011).

1.3.3 Millimeter observations

Interferometry Resolved imaging of the dust continuum at (sub)millimeter wavelengths in the pre-ALMA era has confirmed the presence of dust cavities in about two dozen transition disks with large cavities of 15-75 AU (~0.15-0.65" at 120 pc) to date (e.g Piétu et al. 2006; Brown et al. 2009; Isella et al. 2010a; Andrews et al. 2011; Williams & Cieza 2011). Interferometric arrays such as the PdBI, CARMA and SMA have been used to resolve the structure down to ~ 0.3" diameter resolution. The millimeter images of these SED-selected transition disks show a ring-like morphology, confirming the deficit of dust inside the cavity. In some cases hints of asymmetries were seen, but the signal-to-noise of the images was too poor to conclude whether these asymmetries were significant. Even though their significance was debatable, these asymmetries were already suggested to originate from vortices (Regály et al.

2012). The quality of the images was also low because of the limited u, v-coverage (spatial scales) of the observations, due to the small number of antennas. With the larger number of antennas of ALMA the issues of sensitivity and u, v-coverage are largely resolved for imaging these disks.

The analysis of the pre-ALMA data, using radiative transfer codes, was performed on the interferometric visibilities, which show a Bessel function in case of a ring, where the first "null" (crossing of zero) is a measure of the ring size. The basic modeling structure was a surface density with a sharp dust cavity wall with cavity radii of ~15-75 AU and an empty dust gap, but the dynamic range of the images was limited and the inner disk was set by the SED with all its caveats. Alternative models suggested that a smooth cavity wall fits equally well (Isella et al. 2012) and that some dust may still be present inside the gap (Isella et al. 2010a; Mathews et al. 2012). For some disks it was already known that gas was present inside the cavities as well (e.g. Pontoppidan et al. 2008).

It is important to recognize that modeling disk structure was (and is) not dictated by theoretical models of disk clearing mechanisms, but by a simple parametrization based directly on the observations with limited parameter space due to the large number of uncertainties, both in the data and in the modeling assumptions. However, the deep millimeter cavities could rule out grain growth in the inner part of the disk as a transition disk mechanism: although grain growth in the inner part of the disk results in a dip in the SED, the grains do not grow sufficiently large to stop emitting at millimeter wavelengths (Birnstiel et al. 2012). Interferometric imaging was very time expensive; multiple nights in different array configuration were required to cover sufficient spatial scales and the sensitivity was limited to observations of the brightest disks. With the large number of antennas of ALMA it is now possible to get high S/N images of the millimeter-dust structure within hours.

Dust opacity Millimeter continuum emission is usually optically thin and originates from the cold outer disk. The dust opacity κ_ν represents the level of warm dust emissivity per unit mass, depending on composition, porosity and size distribution $n(a)$ of the dust grains. In general $\kappa_\nu \sim \nu^\beta$, where the spectral index β is sensitive to the maximum particle size in $n(a)$ (Draine 2006). The small dust grains in the interstellar medium have a typical value of $\beta \sim 1.7$. For a dusty disk with a power-law size distribution and a maximum grain size of ~1 millimeter this results in β values lower than 1. At a specific observing wavelength $\lambda_{\rm obs}$, the emission is sensitive to dust particles up to $3\lambda_{\rm obs}$. Although β can not be measured directly, in the Rayleigh-Jeans tail of the SED (where the dust is optically thin), the spectral slope α_{mm} given by $F_\nu \sim \nu^{\alpha_{mm}}$ can be used to derive β using $\beta \approx \alpha_{mm} - 2$. The observational parameter α_{mm} can thus be used as a probe of dust growth.

Observing dust growth The detection of multi-wavelength millimeter emission with low values of β has confirmed dust growth up to at least millimeter-sized grains in protoplanetary disks as the start of planet formation (e.g. Beckwith & Sargent 1991; Andrews & Williams 2005, 2007a; Rodmann et al. 2006; Lommen et al. 2009; Ricci et al. 2010a,b). Dust evolution models predict that in absence of pressure maxima the continuum emission will be radially concentrated due to the radial drift (Birnstiel & Andrews 2014). This has been observed several protoplanetary disks in spatially resolved millimeter observations, indicating a radially increasing spectral slope $\beta(r)$ (Guilloteau et al. 2011; Pérez et al. 2012). The global value of β in transition disks is higher than in normal disks due to the removal of large grains inside the cavity (Pinilla et al. 2014). However, dust growth inside pressure bumps would reveal a local decrease of β in spatially resolved observations at the pressure maximum (Birnstiel et al.

2013). This effect is studied in this thesis for three transition disks using ALMA and VLA observations.

1.3.4 Infrared observations

Infrared imaging has been used to probe the small dust grains in the hot surface layers of the inner part of the disk. The brighter Herbig disks are most suitable for these observations, although some T Tauri stars have been imaged as well. Scattered light or polarimetric imaging in the near-infrared is a particularly useful tool for high spatial resolution images. Polarimetric imaging of transition disks has been done with VLT/NACO (e.g. Quanz et al. 2011; Garufi et al. 2013) and in the SEEDS survey with Subaru/HiCIAO (e.g. Thalmann et al. 2010; Muto et al. 2012; Follette et al. 2013) in H and K bands. These observations have revealed a large variety of features in the small dust distribution: spiral arms, warps, gaps and dips. Remarkably, the dust gap seen at infrared wavelengths, if present, is often smaller than the millimeter-dust cavity. In some cases no gap is seen, although it could simply be smaller than the mask that is used to block the stellar light. Future observations with SPHERE and GPI are expected to reveal even more detail, at < 0.1" spatial resolution. Dust filtration/trapping by a planetary companion has been suggested as a possible reason for the discrepancy between the millimeter/micrometer-sized dust grain cavities (Dong et al. 2012; de Juan Ovelar et al. 2013).

At longer infrared wavelengths the thermal radiation of the cavity wall dominates the dust emission. Mid-infrared imaging with e.g. the VLT/VISIR instrument has resolved dust cavities of several bright transition disks (Geers et al. 2007; Maaskant et al. 2013), including IRS 48, which is used in this thesis as a comparison between small grains and large millimeter grains seen by ALMA. Infrared interferometry with VLTI and the Keck Interferometer provides only limited imaging due to the low u, v-coverage, but by modeling the visibilities it was found that the gaps of a handful of transition disks were indeed largely depleted of dust (Olofsson et al. 2011) and evidence was found for a smooth rather than sharp cavity edge (Mulders et al. 2013).

The combination of infrared and millimeter observations and theoretical models in the last decade have thus shown several hints for dust trapping in transition disks. However, it was not until spatially resolved observations of gas and dust became available with ALMA that clear evidence for dust trapping was found.

1.4 This thesis

The advent of ALMA has revolutionized our view on transition disks, giving unprecedented spatial resolution and sensitivity in (sub)millimeter observations. For the first time, the sensitivity is sufficient to resolve the dust *and* the gas at high S/N, connecting the dots in the complex framework of transition disks. The main questions we aim to answer in this thesis are: What is the gas density structure inside transition disk cavities? What does that tell us about their origin and the properties of any embedded planets? Can we find observational evidence for dust trapping in these disks? What can statistical studies of a broad sample of transition disks tell us about their role in evolution?

In the ALMA Early Science Cycles we requested CO line observations at high spatial resolution (~ 0.25") of several famous transition disks in order to constrain the clearing mechanism. The disks were selected based on previous SMA dust continuum observations and VLT CRIRES CO observations, already indicating the presence of gas inside the dust cavity, which could now finally be quantified through ALMA CO rotational line observations and the modeling program DALI. The first disk studied was Oph IRS 48, a Herbig star in the star forming region Ophiuchus (d=120 pc) with a known micrometer-dust ring at 55 AU from mid-infrared observations. PAHs are found inside this dust cavity and a hot CO gas ring is seen at 30 AU. Subsequently a sample of 7 other disks have been observed and modeled to draw more general conclusions.

- In Chapter 2, the discovery of an azimuthally asymmetric dust trap in IRS 48 is presented through ALMA Band 9 observations of the 690 GHz continuum and the ^{12}CO 6–5 lines. The azimuthal asymmetry came as a total surprise, as the millimeter-dust continuum was only a by-product of the requested line observations. The millimeter-sized dust shows peanut-shaped emission on one side of the disk at 60 AU radius, in contrast with the CO and the mid-infrared emission which are consistent with ring-like emission. The system could be modeled as a disk with a vortex, caused by a Rossby-wave instability of a radial pressure bump generated by a massive planet.

- Chapter 3 and 4 continue the exploration of the dust trap scenario: the concentration of dust grains inside the IRS 48 dust trap is confirmed through spatially resolved VLA observations of centimeter grains. Chapter 4 presents spectral index variations in SR 21 and HD135344B from 345 and 690 GHz ALMA observations, which are compared with dust evolution models to test the validity of the trapping model for these transition disks.

- In Chapter 5, the ^{12}CO 6-5 observations of IRS 48 are modeled in more detail using the physical-chemical modeling code DALI. The gas disk is found to have two drops in the density distribution: one within 20 AU and one within 60 AU, suggesting the presence of multiple planets.

- In Chapter 6 ALMA Early Science observations of six other well studied transition disks are analyzed with DALI to derive the gas and dust density structures. The dust surface density and in particular the cavity size is constrained by a simultaneous fit of the SED and the 690 GHz continuum visibilities. The density drop of the dust inside the cavity is at least a factor of 1000 for all disks. Assuming a gas-to-dust ratio of 100 in the outer disk, the ^{12}CO 6–5 line data are fit using the same surface density model, but with different drops in the gas density inside the cavity. For five of the disks, the drop in gas density is found to be less deep than the drop in dust density, which is consistent with the planet clearing scenario.

- Chapter 7 continues the analysis of gas inside cavities through spatially resolved ^{13}CO and $C^{18}O$ observations of four disks: IRS 48, DoAr 44, SR 21 and HD 135344B. The last two disks were also part of the ^{12}CO analysis of Chapter 6. The CO isotopologues suffer less from optical depth and are more direct column density tracers. For three of these disks, the CO observations clearly show gas cavities smaller than the dust cavities, which is a direct hint of clearing by planets. The observations are compared with the outcome of planet-disk interaction models to estimate the mass of the embedded planets. Also, in this analysis the isotope-selective CO photodissociation model is applied, resulting in a more robust derivation of the disk mass through $C^{18}O$ emission.

- Chapter 8 zooms in on the chemistry in IRS 48. We present the discovery of warm H_2CO in the IRS 48 disk from ALMA observations and set an upper limit on the abundance of this molecule with respect to H_2 of 10^{-8}. Upper limits for several other complex molecules are derived and found to be consistent with full chemical models.

- Finally, in the last chapter, a large SED survey of 200 *Spitzer*-selected transition disk candidates is presented. The candidates are selected using color criteria derived by Merín et al. (2010) from the *Spitzer* catalogs and spectroscopy of nearby star-forming regions. SEDs are constructed from optical, 2MASS and *Spitzer* photometry, complemented by new *WISE*, *Herschel* and (sub)millimeter data. Spectral types are derived from a large optical spectroscopy program. Using RADMC modeling, the SEDs are modeled to infer the cavity sizes. The survey has resulted in at least 70 new candidate transition disks with large inner cavities, that can be followed up by ALMA observations.

Each chapter ends with its conclusions based on the presented data. Overall the main conclusions from this thesis are:

- The first unambiguous evidence for a dust trap in a transition disk has been found through combined micrometer, millimeter and centimeter observations (Chapter 2,3). This discovery confirms theoretical predictions that have been made in the last three decades. This conclusion is strengthened by spatial variations in the millimeter spectral index (Chapter 4).

- All transition disks that have been studied with CO observations in this thesis show that gas is present inside the dust cavity. The gas cavity is smaller than the dust cavity and the gas density drops by a factor of 100-1000. This indicates that planets are embedded in these disks which have cleared their orbit and trapped the millimeter dust in a ring around it (Chapter 5,6,7).

- Color criteria provide a robust method to select good transition disk candidates with large dust cavities from *Spitzer* catalogs (Chapter 9).

1.5 Outlook

ALMA has revolutionized our view of transition disks, making a direct connection with dust trapping models and zooming in on the gas structure inside the dust cavities. The observations presented in this study were taken in ALMA Early Science, with baselines of less than 1 kilometer. In the coming years observations will be taken with very long baselines up to 10-15 kilometers, providing spatial resolution of milliarcseconds, such as shown in the astonishing image of dust rings in the HL Tau disk (ALMA Partnership et al. 2015).

Observing other transition disks at such high resolution will allow us to measure the gas structure to much better detail, constraining the shape of the gaps to the precision of theoretical disk models and resolving dust and gas cavities as small as a few AU. Direct detection of planets inside disks remains challenging, but has been done in a few cases (Huélamo et al. 2011; Kraus & Ireland 2012; Quanz et al. 2013; Reggiani et al. 2014; Quanz 2015). Measuring the shape of the gas cavity will allow us to determine properties of embedded planets indirectly, leading to the earliest view on these recently formed planets. The high spatial resolution will allow the detection of circumplanetary disks as well, another indirect method of detecting planets in a disk. ALMA also has the sensitivity to observe less massive transition disks, so the sample is no longer restricted to the brightest known disks studied so far. Measuring cavities down to a few AU radius and disk masses down to less than a Jupiter mass means a much more complete picture of transition disks, which will give us a better understanding of their origin. Are multiple mechanisms responsible for the cavities? Are there different classes of transition disks? What role do transition disks play in the disk dispersion process?

Multi-wavelength observations of the dust continuum at high spatial resolution will give further constraints on dust growth in disks, by measuring spectral index variations as a function of position in the disk. The Band 9 observations that were used in this thesis to show spectral index variations have the limitation that the dust is likely optically thick at this wavelength. With the longer baselines of ALMA, high spatial resolution can be achieved also at longer wavelengths where the dust becomes optically thin. The ongoing Disks@EVLA key program will observe 66 disks at centimeter wavelengths, which can be compared directly with millimeter observations. The multi-wavelength approach provides information on dust grain sizes in disks, which is crucial for dust evolution theories and understanding the start of planet formation.

Large disk surveys of Class II and Class III objects with ALMA in gas and dust may finally connect the link between the gas-rich primordial disks and gas-poor debris disks: ALMA observations of a handful of bright debris disks have already revealed that gas is still present in some of these disks, possibly second-generation gas due to icy planetesimal collisions (e.g. Kóspál et al. 2013; Dent et al. 2014). Perhaps transition disks and debris disks are more closely linked than previously thought.

Finally, the ALMA sensitivity will increase further, and some complex molecules are expected to be detected in disks in the coming years (Öberg et al. 2015). Knowing the chemical composition of disks will answer important questions about the composition of exoplanet atmospheres and, ultimately, the origin of life.

Other telescopes and instruments will also contribute to an even better understanding of transition disks. The VLT SPHERE instrument has just started operations, creating beautiful scattered light images of the small dust grains in disks at less than 0.1" resolution that can be compared directly to the millimeter dust in ALMA observations. Infrared spectroscopic observations with future facilities such as the *James Webb Space Telescope*, the *European Extremely Large Telescope* and the *Thirty Meter Telescope* will zoom in on the hot inner regions of disks, providing even more information on the gas dynamics close to star where planets are expected to form.