Observational constraints on the evolution of dust in protoplanetary disks

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Introduction

According to data from the Wilkinson Microwave Anisotropy Probe (WMAP) experiment, the universe came into existence roughly 13.7 billion years ago (Spergel et al. 2003). Modern cosmology suggests that the universe remained a dark place for much of its first billion years, the “dark ages”. During this time, the universe consisted of dark matter, as well as clouds of neutral hydrogen gas and little else. The first stars did not form until several hundred million years had passed (Bouwens & Illingworth 2006; Salvaterra et al. 2006). However, once the cosmic star-making machinery ignited, it agitated giant balls of gas into lots of stars that formed the first galaxies. It is now thought that the observable universe contains 10^{21} stars. Cosmic star formation is the dominant mechanism that controls the visible structure of galaxies and the build up of heavy elements in the universe with time. Originally, the only elements were hydrogen, helium, and traces of lithium, beryllium and boron. Heavier elements did not yet exist.

Stars are born, evolve and age, and eventually die. In simple terms, they are born from collapse of molecular clouds and may evolve differently during their lifetime, depending on their masses. During its evolution, a star burns light elements into heavier ones through nuclear fusion, thereby producing the energy necessary to balance the inward gravitational pressure and keep itself alive. During the course of their evolution, stars change mass (through accretion or mass loss), size (expansion or collapse) and luminosity (a change of thermonuclear reactions in their cores). Stars can be single and isolated or, very commonly, live in multiple systems. When a star has used up its nuclear fuel, its radiation pressure can no longer balance its gravity, setting in motion a chain of irreversible processes that eventually lead to its death. Stars of modest mass eject their gaseous envelope and become visible as planetary nebulae, while the more massive ones explode as supernovae. Freshly synthesized heavy elements (including Si, O, C, Mg and Fe, that make up the dust particles from which planets may eventually form) are thus ejected into space, where they intermingle with the surrounding Interstellar Medium (ISM). This "enriched" ISM subsequently provides the material for the next generation of stars, eventually leading to the creation of the planetary systems in which life in the universe has become possible.

In our own Milky Way, one theory is that a supernova explosion has triggered the formation of our Sun and its protoplanetary disk, around 4.6 billion years ago (e.g., Cameron 1962). Eight planets (Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune) and countless smaller bodies (e.g. dwarf planets, comets, asteroids) were formed from the material in this pre-solar nebula. The structure and composition of these Solar System bodies has given the first clues to the development of models of how planets are formed.

This thesis focuses on the interplay of the young star and its protoplanetary disk, on the evolution of the dust particles that make up the protoplanetary disk surrounding the young star, and thus on the very first stage of the formation of planets like those that compose our own Solar system.

1.1 Low-mass Star Formation

The most common type of stellar objects are stars of low mass ($\sim$0.5 $M_\odot$), that dominate both in number and in total mass. Low-mass stars form inside relatively dense concentrations of interstellar gas and dust known as molecular clouds (Stahler & Palla 2004), with the dust making up $\sim$1 % of the mass of the cloud (Tielens 2005). This dust is believed to be sub-μm in size and to consist of almost completely amorphous silicate- and carbon-based grains (Kemper et al. 2004). These regions are mostly self-gravitating, confined by an external pressure, magnetized and extremely cold ($T \sim$ 10 K). Under these conditions, most elements are in molecular form, as revealed by observations of CO emission (Ungerechts & Thaddeus 1987). These dense regions are opaque to visible light due to their high extinction, but translucent at longer wavelengths. Therefore observations at longer wavelengths can probe the internal structure of clouds and study star formation.

Star formation begins when a region in the cloud cools and reaches a sufficient density of matter to satisfy the criteria for Jeans instability, beginning to collapse under its own gravity (Shu et al. 1993; Myers et al. 2000). Matter accretes toward the center at a constant rate. As the gas and dust contract from the inside-out (Shu 1977), gravitational energy is released through radiation and quickly re-absorbed by the opaque envelope of material that is still collapsing. Short wavelength radiation from deep inside the core is then obscured when captured by the dust in the envelope, reprocessed and re-emitted at infrared or sub-millimeter wavelengths, thereby providing information on the dusty outer environment. Furthermore, when gravitational energy is transformed into kinetic energy during the collapse, gas particles speed up and collide, increasing the temperature of the forming star and its immediate surroundings. As a result, thermal pressure builds up, which serves to support the cloud structure against further collapse.

As the cloud fragment shrinks due to gravity, conservation of angular momentum leads to a spin-up of the inner parts of the core. Collapse keeps occurring, preferentially along the path of least rotation. Finally, the cloud fragment collapses into a central core surrounded by a rotating disk of material. This central core, a "protostar" and its disk, keeps accreting material from the surrounding envelope. Stellar winds (e.g. X-winds, disk winds) break out along the rotational axis of the system, reversing infall and sweeping up material into two outwardly expanding shells of gas and dust, known as "bipolar outflows" (Snell et al. 1980; Bachiller & Tafalla 1999) while infall still occurs in the equatorial regions. With time, the outflow angle opens up, eventually terminating the infall and revealing the newly-formed star. This pre-main sequence star, surrounded by a circumstellar disk, has now become visible at optical wavelengths. This phase is known as the "T Tauri" phase. The entire star-disk-envelope-outflow system is called a young stellar object (YSO).

At this pre-main sequence stage, the optically visible low-mass star is still contracting toward the main-sequence (MS) on a radiative time scale. With interiors not yet hot enough to burn hydrogen, deuterium burning plays an important role in the early stages of stellar evolution. Due to the stellar contraction, the internal temperature incessantly rises, until it reaches $\sim 10^7$ K, at which point hydrogen fusion begins. At this moment the star is said to be on the *zero-age main-sequence* (ZAMS). The ZAMS marks a locus in the *Hertzsprung-Russell* (H-R) diagram corresponding to a relation between the luminosity of a star and its temperature.

T Tauri stars are known for their excess emission, i.e., beyond that produced by the stellar photosphere. The presence of prominent optical emission lines such as Hα reveal the presence of both outflowing and infalling matter, while their excess continuum radiation at infrared wavelengths furnishes evidence for the existence of circumstellar disks. This infrared excess is understood as reprocessed stellar radiation by the circumstellar disk, which is composed of dust and gas. Actively accreting disks will also produce excess radiation, mostly in the UV regime, and broad emission lines. Because stars and their disks are connected, they evolve together and will affect each other.

Another fundamental characteristic of T Tauri stars is their temporal variability – line and continuum fluctuations that span a range of amplitudes and can be either random or periodic. T Tauri stars are further divided into two subclasses: classical T Tauri stars (CTTS) and weak-line T Tauri stars (WTTS). WTTSs are low-mass pre-MS stars that occupy the same region of the H-R diagram as CTTSs but do not show clear evidence of accretion. The distinction between the two is usually made based on the Hα equivalent width (EW). Since there is a very strong correlation between spectroscopic signatures of gas accretion and the presence of near-IR excess (Hartigan et al. 1995), most CTTSs show near-IR excess while most WTTSs lack such an excess.

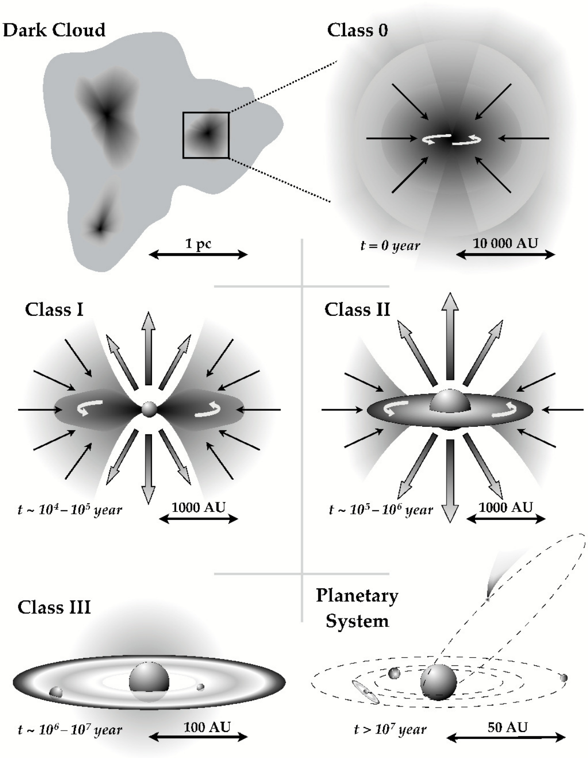

Figure 1.1 – Illustration of the scenario for low-mass star formation, as described in the text (Frieswijk 2008, after Shu et al. 1987). The formation of dense cores occurs in molecular clouds (upper left), and the core collapse under its own gravity (upper right). As the surrounding envelope starts to dissipate, strong bipolar outflows remove angular momentum (middle left) until the newly formed star and its circumstellar disk become visible (middle right). As gas dissipates, giant planets should already be formed (bottom left). By the time the entire disk has dissipated, the possible planetary system around this star should have completely formed (bottom right).

1.2 Stellar Properties

To study the structure and evolution of protoplanetary disks, and how these connect to their host star, it is of prime importance to be able to determine stellar properties. A star of a given temperature emits radiation roughly as a black-body of that temperature. Radiation emitted by massive stars peaks at shorter wavelengths (UV/visible) than that emitted by low-mass stars (visible/near-IR). Consequently, the visible/near-IR regime is the optimal wavelength range to observe T Tauri stars.

By studying the optical spectra of stars of different surface temperatures, it is possible to define temperature-sensitive features that have historically been used to determine their effective temperature. These absorption bands are more prominent in the spectra of cooler stars and, due to their width, they can be detected even in low-resolution spectra. By comparing the appearance and strength of these temperature-sensitive features with those of stars of different known temperatures (templates), one can determine the spectral type of the star in question. Besides temperature, the analysis of a stellar optical spectrum also allows the determination of its surface gravity, rotational velocity, and metallicity. These quantities, however, are best (and sometimes only) determined with medium- to high-resolution spectroscopy. If the distance to the star is known, the stellar luminosity can be derived directly through flux measurements in different bands. The stellar mass, radius, and age can be estimated based on stellar models. The derivation of stellar parameters from optical spectroscopy is the subject of two chapters in this thesis.

Ages of pre-MS stars, however, are very difficult to determine due to our limited understanding of stellar structure and evolution during the pre-MS stage (Hillenbrand 2009). Different models of stellar evolutionary tracks in the H-R diagram vary considerably, depending on the choice of input physics used. These variations lead to different ages being inferred for the same object, when using different tracks. Furthermore, it has been suggested that the accretion history of an object, which may be episodic, should be taken into consideration when using stellar tracks to age a pre-MS star (Baraffe et al. 2009). This poses a great difficulty for exact age determinations, as no object has been monitored for millions of years. For these reasons, mean cluster ages are often considered to be a better clock than individual ages.

1.3 Protoplanetary Disks and Planet Formation

The origin of planets is naturally connected to the evolution of the protoplanetary disks from which they formed. However, the details of how exactly disks evolve from their initial composition consisting of small dust grains coupled to the gas into complex planetary systems are not yet understood. While virtually all young stars have such disks, most older MS stars show no signs of being surrounded by disks. This constraint implies that disks must evolve, either by accreting or dispersing dust and gas, or by building-up larger bodies.

1.3.1 Disk Properties

Once the envelope surrounding the forming star is dispersed, the now observable circumstellar disk can be studied directly. Observations have shown disks initially to be good mixtures of dust and gas (dust-to-gas mass ratio $\sim$0.01), flared and extending several hundreds of AU in radius. Despite its low abundance, the dust dominates the disk opacity.

1.3.1.1 Disk Observations

The solid material that composes a protoplanetary disk is exposed to the radiation from the central star, and a possible accretion source. The dust, besides absorbing some of the radiation, also re-processes and re-emits a part of it. In fact, the main observational constraint on the existence of protoplanetary disks is the observation of an excess of radiation at IR and (sub-)mm wavelengths that can not be attributed to the star alone. With the current observational facilities, only the few closest disks can be directly imaged. Therefore, the existence of disks is often inferred indirectly from the existence of an IR-excess observed toward a star.

Because the Earth's atmosphere absorbs most of the light in the infrared regime, ground-based infrared observations are impossible at some ranges. For this reason, a lot of effort has been put into launching infrared space telescopes. Most of the data presented in this thesis were obtained using the *Spitzer Space Telescope* (Werner et al. 2004). *Spitzer* was launched in 2003, and operated in full capacity until the summer of 2009, when its cryogenic mission ended. After running out of the Helium supply that kept the telescope cooled, *Spitzer* continues to produce data in its 'warm mission', albeit in only two filters. The telescope is composed of three instruments: the InfraRed Array Camera (IRAC, photometry at 3.6, 4.5, 5.8 and 8 μm), the Multiband Imaging Photometer for Spitzer (MIPS, photometry at 24, 70 and 160 μm), and the InfraRed Spectrograph (IRS, spectroscopy from 5 to 40 μm at $\lambda/\Delta\lambda \sim$ 50–100 and 600). These wavelengths are used to probe protoplanetary disks at different radii, thereby providing constraints on their structure ranging from the inner to the mid-disk.

1.3.1.2 Star-Disk Interactions

Because stars and their disks are physically connected, a complete understanding of these complex systems can only be gained by studying both objects together. This can be done by studying the spectral energy distribution (SED) of the system. The SED is a plot of flux (λF_λ) versus wavelength, comprising a wide wavelength range. For stars with disks, the stellar photosphere contributes most to the emission at short wavelengths, i.e. in the UV and optical, while the disk is responsible for most radiation at longer wavelengths, i.e. in the IR and (sub-)mm. Although a protoplanetary disk can produce its own energy through accretion, for most cases this amount is small when compared to the stellar luminosity. This way, the discussion presented here can be generalized for passive disks. In this case, the stellar radiation field defines the temperature of the dust in the disk, which can be modeled using dust radiative transfer codes that relate the observed SEDs to the structure of the system. Hence, the SED shape yields the structure of the disk, while the long wavelength flux gives its total mass.

SEDs are an important tool in the study of stars with disks and, together with direct imaging observations, a great deal has been learned about those systems. The warm disk surface layers and disk inner rim, close to the star, are responsible for the emission at shorter IR wavelengths. Deeper into the disk, probing now a colder dust population, the dominant emission is at longer (far-IR and mm) wavelengths (Figure 1.2). From this basic understanding, it becomes clear what the results would be from suppressing or enhancing any of these components. In reality, however, SEDs are degenerate and interpreting them is neither easy or trivial. Still, SEDs are important tools in the study of protoplanetary disks, and a lot can be learned from them. A disk depleted of dust and gas (that has either accreted toward the star, been blown away by its radiation, or coagulated into big bodies) will present very little or no excess radiation. Additionally, the presence of a gap (star-disk-gap-disk) or hole (star-hole-disk) in the disk will produce very peculiar signatures in the system's SED by suppressing the radiation at short IR wavelengths that the small dust would have produced.

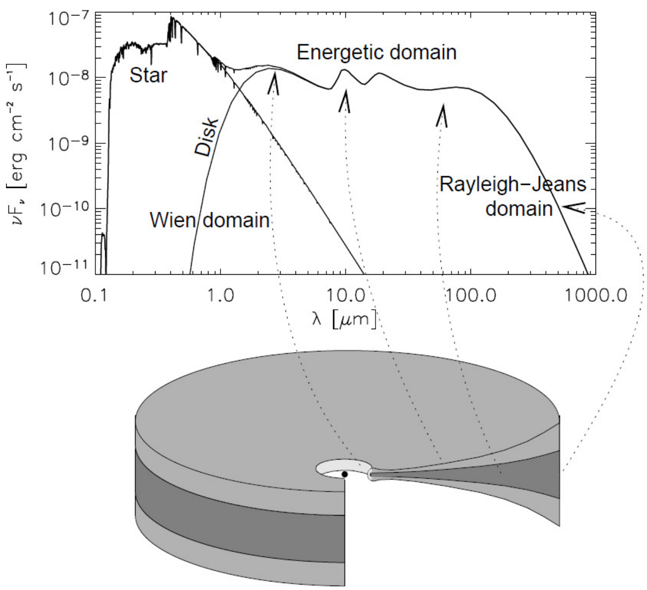

Figure 1.2 – Build-up of the SED of a flaring protoplanetary disk and the origin of its different components: the near-IR emission comes from the inner rim, the mid-IR dust features are emitted by the warm surface layer, and the underlying continuum from the deeper (cooler) disk regions. Typically the near- and mid-IR emission comes from small radii, while the far-IR comes from the outer disk regions. The (sub-)mm emission mostly comes from the midplane of the outer disk (Dullemond et al. 2007).

Furthermore, dust features can be seen overlaid on top of the dust continuum emission. In the IRS regime, polycyclic aromatic hydrocarbon (PAH) and silicate features (at 10 and 20 μm) are very prominent, and can probe the physical and chemical processes affecting the warm dust in the surface layers of the inner regions of the disk, as it is shown in two chapters of this thesis.

1.3.1.3 Processes Affecting the Disk

The evolution of disks is a combination of external and internal processes. Being the main source of radiation of the system, the central star affects the disk dispersal directly. Stellar winds can sweep-up and remove some of the disk material. Furthermore, energetic UV and X-ray photons emitted by the central star (or a massive nearby star) heat the disk surface and cause thermal pressure-driven hydrodynamic mass outflows from the disk. This process is called *photoevaporation* and, in combination with the viscous evolution of disks, has been shown to be a very effective mechanism for the dispersal of disks (Hollenbach et al. 2000; Clarke et al. 2001; Alexander et al. 2006a,b; Ercolano et al. 2009; Górny et al. 2009; Owen et al. 2010). Depending on the energy of the photons, they can be responsible for opening inner gaps in those disks, or inducing mass outflows in the outer disk, where most of the mass resides.

While some material is being expelled from the disk, accretion flows onto the star continue. The inner disk is disrupted by the stellar magnetic field, resulting in magnetospheric accretion, in which disk material is channelled along the magnetic field lines into the star (Koenigl 1991). This material infall produces high temperature optical and UV continuum emission and strong emission lines, the strongest of them being Hα (Calvet & Hartmann 1992).

In addition to the external processes described above, theory, observations and laboratory experiments point to processes that affect the dust inside disks (Weidenschilling 1980; Dominik & Tielens 1997; Blum & Wurm 2008) and thereby also the disk structure (Dullemond & Dominik 2004). The high disk densities facilitate particle collision and dust coagulation. As they grow larger, particles settle gravitationally towards the disk midplane, making it an even denser environment and therefore more prone to further growth into roughly km-sized bodies called *planetesimals*. These steps are the early stages of planet formation. Observationally, particle coagulation is equivalent to the removal of the small dust component, manifesting itself as a flattening of the disk and a decrease of the infrared excess of a disk (Dullemond et al. 2001).

Debris disks, composed of large planetesimal rocks and smaller bodies that are produced in situ by collisions of planetesimals, have been found around both evolved and young stars (Rieke et al. 2005; Su et al. 2006; Gautier et al. 2007; Wyatt 2008; Carpenter et al. 2009). This phase is understood to follow the protoplanetary disk phase, when gas is no longer present.

1.3.2 Planet Formation

Because the very small dust grains that initially compose a disk are coupled to the gas, they move slowly (few cm s^{-1}) in Brownian motion. These low velocities allow grains to grow via pairwise collision in regions of high disk densities (Blum & Wurm 2008). Bigger particles settle faster to the disk mid-plane where, in a similar fashion, particles will continue to coagulate. In this manner particles may grow up to meters in size, at which point their dynamics begin to decouple from the gas. No longer being coupled to the gas, the motion of these planetesimals is dominated by gravitational forces, following Keplerian orbits and moving faster than the gas. Those particles then feel a headwind from the interaction with the slower moving gas, losing angular momentum. The loss of angular momentum causes the particles to drift inward. This radial drift is very fast, especially for particles of ∼1 meter in size, such that the planetesimals quickly reach the evaporation zone and vaporize (e.g. Dominik et al. 2007). This is a major problem, referred to as *the meter-size barrier*, and any model that relies on aggregational growth from dust to planets must pass this barrier within the timescale that would take for these bodies to drift in.

One way to overcome this problem that has been recently explored in the literature is with streaming instabilities (e.g. Youdin & Goodman 2005; Johansen et al. 2007). In these models the roughly m-sized particles, after concentrating in pressure maxima regions in the turbulent gas in the disk, can grow an order of magnitude by streaming instabilities driven by the relative flow of solids and gas. This collapse is found to be faster than the radial drift timescale, therefore allowing those particles to survive the meter-size barrier and possibly grow further into planets.

The further growth from planetesimals into planets is not yet well understood. To make matters more complicated, objects with sizes in the range $10^{-1} - 10^{5}$ m cannot be observed directly. Two different models have been introduced to explain the formation of planets (thousands of kilometers in size). The *core-accretion* model (Safronov & Zvjagina 1969; Goldreich & Ward 1973; Pollack et al. 1996) suggests that further growth beyond km size happens gradually, as the coagulation works for small particles. Planetesimals interact gravitationally, accreting onto each other to form a heavy-element core. Once this core is massive enough, its gravitational field captures gas to create a gas giant. Alternatively, the *disk instability* model (Cameron 1978; Boss 1997) suggests that dense clumps will be formed by fragmentation of the disk. These clumps contract to form planets much like the formation of stars by the collapse of a molecular cloud clump. Although the core accretion model is favored by most theorists, both models have advantages and problems. The core accretion model may take too long to form a core massive enough to capture gas, such that by then the gas has already dissipated from the disk. For the disk instability model to work, disks must be more massive than observations seem to suggest.

1.3.3 The Solar System & Exoplanets

Observations of an increasing number of stars have shown that the Solar System is not unique, and that planets and planetary systems come in a variety of forms. The origin of this variety is still unclear, but must be connected to their formation processes.

Planets and planetary systems seem to be a rather common output of disk evolution, and have been observed around hundreds of stars other than the Sun (Udry & Santos 2007). This, however, does not seem to be the only output of disk evolution. Some MS stars present debris disks and, although it is still unclear whether debris disks often also harbor planets (Kóspál et al. 2009), this is true for at least a few of them (e.g., β Pictoris and Fomalhaut, Lagrange et al. 2010; Kalas et al. 2008). However, most MS stars show no signs of planets or debris within the current observational limitations, meaning that disks around such stars were completely dispersed, leaving no dust behind to tell the story.

Since the landmark discovery of a planet orbiting the solar-like star 51 Peg around 15 years ago (Mayor & Queloz 1995), the $\sim$500 exoplanets detected to date form a powerful database of the possible end-products of disk evolution. Follow-up studies of planet-host stars have shown that stars that harbor planets are consistently more enriched in metals than those that have shown no sign of orbiting planets (Fischer & Valenti 2005; Udry & Santos 2007). If true, this relation must either be a natural consequence or the direct cause of planet formation. Additionally, the distribution of planet masses and orbital positions in relation to the host stars offer further observational constraints for planet formation models.

Only one planetary system, namely our own Solar System, has been studied to the level of detail necessary to provide reliable information on dynamics and composition of its constituents. Remarkably, our Solar System contains a collection of ancient remnants that have preserved the material that composed the early solar system in virtually unaltered form for over 4.5 Gyr. Analysis of chondritic meteorites and interplanetary dust particles, as well as observations of comets, have revealed their structure and mineralogy, pointing to important physical and chemical processes that took place during the early evolution of the protoplanetary disk around the young Sun. For instance, it has been found that these bodies are composed of considerable fractions of crystalline material (Wooden et al. 2007; Pontoppidan & Brearley 2010, and references therein). Looking for clues on how and when such changes occur in the early stage of protoplanetary disks, when planets are still forming, is a very active field of research, and the subject of Chapter 6 in this thesis.

1.4 Disk Diversity and Evolution

In the following, a more detailed background on the main topics of this thesis is presented: disk and dust evolution.

The launch of *Spitzer* represented a major step forward in the study of circumstellar disks. Although many disks had been successfully observed from the ground and space (e.g., with the *Infrared Space Observatory, ISO*), the sensitivity and mapping capability of *Spitzer* allowed the observation of extremely large numbers of systems. Thanks to the statistically relevant disk samples observed by *Spitzer*, complemented by UV, optical and (sub-)mm data, a previously unknown variety of disk structures and timescales has been revealed.

Before *Spitzer*, the global understanding of disk evolution was very much based on evidence from a small number of sources. Thus models for disk evolution and planet formation were derived from: i) extrapolation of characteristics of the few brightest disks as universal; ii) evidence from our own Solar System, and the “solar nebula” from which it originated; iii) observational evidence for disk dissipation within some few Myr. The dominant pre-*Spitzer* view was that disks evolve steadily with time, with material either accreting onto the central star, being dissipated by the stellar radiation, or coagulating into bigger and bigger particles that sink to the midplane.

One of the most important parameters for the formation of giant planets is the gaseous disk lifetime. However, since small dust is well coupled to the gas and since dust is an easier observable, disk lifetimes are often derived just from the infrared excess. The clock of circumstellar disks is the age of its central star. Using the mean age of a cluster and measuring the near-IR excess of its members, Haisch et al. (2001) showed that the fraction of stars surrounded by disks decreases steadily with mean age, concluding that time is an essential parameter in disk evolution. Since then, with much more comprehensive disk observations, several authors have revisited this relationship (e.g. Hernández et al. 2008; Magnelli et al. 2009) without much change in the results: by 6 – 8 Myr only less than 10% of stars in a given cluster still have disks. Although this irrefutably presents time as an important parameter, it is not the only one. Within a cluster of a given age (whether a young, 1 Myr cluster, or an older, 7 Myr one), a great diversity in infrared excess (and therefore amount of dust still present in the disk) is seen. It is still not clear why some disks are completely dissipated by 1 or 2 Myr, while others may live up to 10 Myr.

Many other parameters have been suggested to play an important role in the evolution of disks. For instance, Carpenter et al. (2006) and Kennedy & Kenyon (2009) show evidence of different disk lifetimes depending on the mass of the central star (quicker dispersal for disks around higher mass stars). A diversity of stellar temperatures, luminosities and masses among young stars has been known and studied for decades. Indeed, since stars and disks are connected, it is unlikely that differences in the central sources will not be reflected in their surrounding matter. However, to date no strong evidence has been found as to which processes are determinant on setting the timescale in which a disk will dissipate.

Observations of large disk samples have shown that disks in the same cluster, with same assumed age, show very distinct shapes, structures and masses (Furlan et al. 2006; Sicilia-Aguilar et al. 2006; Oliveira et al. 2010). Different amounts of excess infrared radiation, and at different bands, yield different structures for disks. A strong excess is interpreted as a geometrically flared disk, while little excess suggests a flat, almost dissipated disk. A few disks show little or no near-infrared excess, but otherwise a normal disk, with a significant excess at longer wavelengths. These are interpreted as inner gaps or holes (Calvet et al. 2002). Indeed, sub-mm observations of such disks have shown that a gap without small dust really exists, reinforcing the use of the amount of infrared excess as an indicator of disk geometry (Brown et al. 2007). A difference in geometries is demonstrated by a large sample of classical and weak-line T Tauri stars, as well as debris disks, by Cieza et al. (2007). The distribution of excess slope ($\alpha_{\rm excess}$) changes as a function of the wavelength where the excess starts ($\lambda_{\rm turn-off}$). If grains were to simply grow and settle, $\alpha_{\rm excess}$ should become increasingly smaller for longer $\lambda_{\rm turn-off}$. However, Figure 1.3 suggests that a range of possible processes is responsible for inner disk clearing, which could then be responsible for disks following different paths of evolution.

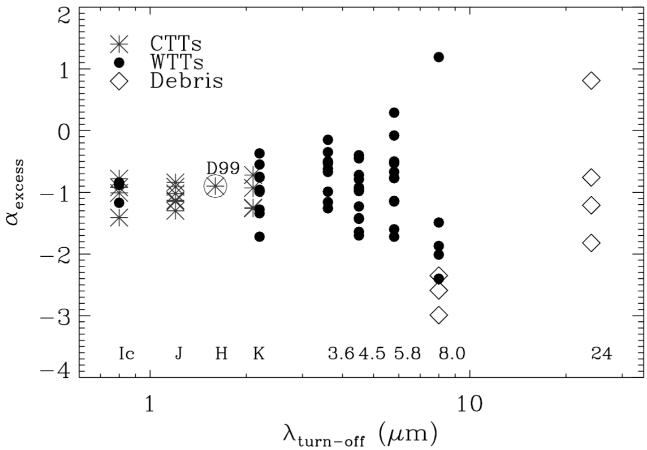

Figure 1.3 – Distribution of excess slopes $\alpha_{\rm excess}$ vs. the wavelength $\lambda_{\rm turn-off}$ at which the infrared excess begins for a sample of WTTSs (filled circles), CTTSs (asterisks) and debris disks (diamonds). The diagram shows a much larger spread in inner disk morphologies of WTTSs with respect of those of CTTSs (Cieza et al. 2007).

As the birthplace of planets, the gas-rich protoplanetary disks have the potential to answer many of the questions related to planet formation. Statistical samples of protoplanetary disks are necessary to identify the environmental and initial conditions of disks, as well as the main processes that affect the evolution of the dust and control the outcome of disk evolution. It has become clear that not all disks evolve in the same manner; however which different paths are possible, and why, is still a mystery.

1.5 Evolution of Dust in Disks

If planetary systems are to be formed, the originally sub-μm-sized, almost completely amorphous ISM dust grains must be transformed into much larger bodies inside protoplanetary disks. A tremendous growth is expected: ∼14–15 orders of magnitude in size, and around 40 orders of magnitude in mass. That is in addition to the complicated chemistry that must take place to create the organic molecules from which life on Earth originated. At least some of these chemical processes happen inside protoplanetary disks, as suggested by observations of primitive Solar System bodies.

1.5.1 Grain Growth

Theoretically, the growth from small to intermediate km-sized planetesimals is fairly well understood. However, these same calculations predict this growth to be a very fast process ($\sim 10^5$ yr, Weidenschilling 1980; Dullemond & Dominik 2005). Therefore, if grains were to grow orderly and uninterruptedly, small dust should no longer be present in disks that are a few million years old. The observation of hundreds of disks in the 1 − 10 Myr range pleads against such a scenario. Instead, these small dust observations imply that they are also created during the evolution of disks. At the same time that collisions favor coagulation, collisions can also be destructive rather than constructive, if the relative velocity between particles is too high (Paszun & Dominik 2009). This fragmentation of bigger bodies can create particles small enough to be mixed with the gas and be brought to the disk surface by turbulent mixing. Fragmentation can explain the presence of small dust in disks for millions of years.

The shape and strength of the silicate features probed by the IRS spectra at 10 and 20 μm are affected by the composition, size and structure of its emitting dust. Because most protoplanetary disks are optically thick at optical and IR wavelengths, the silicate features observed in the mid-IR are generally emitted by dust in the optically thin disk surface only.

A relationship between the size of the grain and the strength and shape of the 10 μm silicate feature was first shown for Herbig Ae stars (van Boekel et al. 2003). Since then, this relationship was shown to hold for lower mass stars, all the way to the brown dwarf limit (e.g., Kessler-Silacci et al. 2006; Apai et al. 2005). ISM-like grains, $\sim$0.1 μm in size, emit silicate features that are strong and very triangular. As the grain size increases, the emitted silicate features appear more flattened and less peaked. By comparing the observed feature with synthetic features calculated for different grain sizes, it is possible to infer the dominant dust grain size opacity in the surface of disks (Figure 1.4). This process is not without its challenges, since the composition of the dust grain also affects the shape of the silicate features. This discussion, and ways to overcome this degeneracy, is the subject of two chapters in this thesis.

1.5.2 Mineralogy

Changes in composition and lattice structure of dust grains have been inferred from the observation of large fractions of crystalline material in primitive Solar System bodies and in protoplanetary disks. Spectra taken from the ground and from *ISO* gave the first clues of a potential link between crystalline material in protoplanetary disks and comets. A great similarity was noted between the spectra of the disk around the Herbig star HD 100546 and that of comet Hale-Bopp (Crovisier et al. 1997; Malfait et al. 1998). Amorphous silicates show broad smooth mid-IR features, while the opacities of crystalline species, such as forsterite and enstatite, show sharp features due to their large-scale lattice arrangement, such that even small fractions of crystalline grains produce additional structure in the silicate features (van Boekel et al. 2004; Min et al. 2005; Bouwman et al. 2008; Juhász et al. 2009, 2010; Olofsson et al. 2010).

According to our current understanding, the way to re-organize the amorphous lattice of a grain into one that is crystalline is through heating. Two main methods

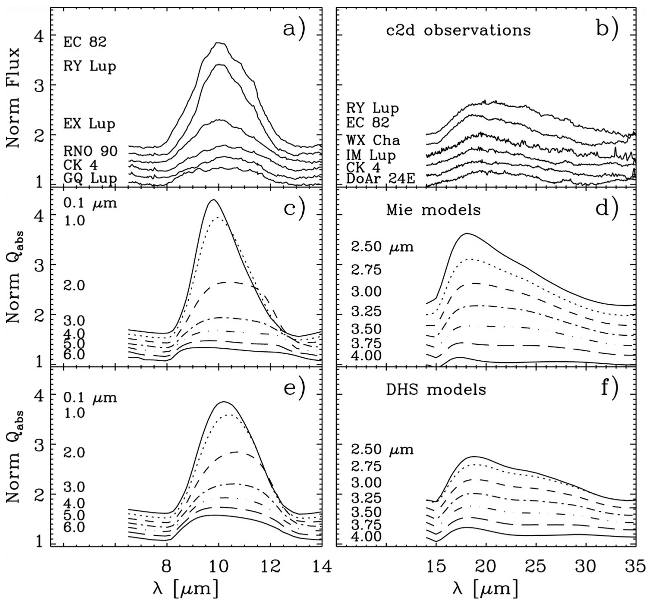

Figure 1.4 – Evidence of grain growth in the Si–O stretching and O–Si–O bending mode features. The top panels show the observed normalized spectra in the (a) 10 μm and (b) 20 μm regions for sub-samples of our sources. The bottom two panels show the normalized absorption efficiencies (Q_{abs}) for models of spherical grains of amorphous olivines with various grain sizes calculated for the 10 and 20 μm regions. Models of filled homogeneous spheres calculated using Mie theory are shown in (c) and (d), and models of hollow spheres calculated using distribution of hollow spheres (DHS) theory are shown in (e) and (f) (Kessler-Silacci et al. 2006).

have been proposed to explain this formation of crystal grains: thermal annealing of amorphous grains or vaporization followed by gas-phase condensation. Both methods require high temperatures (above ∼1000 K, Fabian et al. 2000; Gail 2004), meaning that either method could work in the inner parts of disks, where temperatures are high enough. Yet, observations show crystalline grains over the entire extent of disk surfaces covered by IR observations (van Boekel et al. 2004). Large-scale radial mixing has been invoked to explain the presence of crystals at low temperatures in the outer disk (Bockelée-Morvan et al. 2000; Gail 2004; Ciesla 2009). A third proposed formation mechanism for crystal formation is that of shock waves, which could locally heat amorphous silicates and crystallize them (Desch & Connolly 2002; Harker & Desch 2002).

Mineralogical studies of Solar System bodies show a range of crystallinity fractions. Evidence from primitive chondrites shows that the abundance of crystalline silicate material varies from nearly nothing to up to 20 – 30 % (e.g. Acfer 094 and ALH77307, Pontoppidan & Brearley 2010 and references therein). Oort cloud comets, with long periods and large distances from the Sun, have inferred crystallinity fractions up to 60 – 80 % (e.g. Hale-Bopp, Wooden et al. 1999, 2007). Jupiter-family, or short period comets, have lower fractions, up to ∼35 % (e.g. 9P/Tempel 1, Harvey et al. 2007b; 81P/Wild 2, Zolensky et al. 2006). This discrepancy in fractions points to the existence of a radial dependence in crystallinity fraction in the protoplanetary disk around the young Sun (Harker et al. 2005). Even when considering the discrepancies, the crystallinity fractions derived for Solar System bodies are appreciably higher than those derived for the ISM dust (< 2%, Kemper et al. 2004). One of the conclusions of this thesis is that the observation of crystalline features in protoplanetary disks suggests that the crystallization occurs early in the disk evolution and is then incorporated into larger solid bodies.

1.6 This Thesis

This thesis presents unbiased surveys of low-mass young stars and their dusty disks in nearby star-forming regions using optical/infrared telescopes to probe the evolution of dust in protoplanetary disks. It addresses the full star-disk system: the stellar characteristics and their effect on disk evolution, as well as the changes taking place in the dust itself by making use of statistically relevant samples. The structure of this thesis is as follows:

Chapter 2 – In this chapter an optical spectroscopic survey designed to characterize the new young stellar population discovered in the Serpens Molecular Cloud by the *Spitzer* c2d program is presented. Spectral types, and therefore effective temperatures, are derived from the spectra. Combined with optical and IR photometry, the stellar luminosities are calculated, which allows the placement of these stars in a H-R diagram. Various methods are devised to distinguish true young stellar objects in the cloud from other reddened sources. The contamination from background objects (reddened stars, galaxies) is found to be quite high (25%), raising caution when using IR colors to identify YSOs in low latitude clouds. Aided by evolutionary stellar tracks, ages in the range of 2–6 Myr and masses of 0.2–1.2 $M_{\odot}$ are inferred for the stars belonging to the cloud, if its distance is taken to be 259 pc. Furthermore, mass accretion rates are estimated from the full width at 10% of peak intensity of the Hα line in emission, showing that a bit more than half the sample (57%) is actively accreting.

Chapter 3 – Here we report on an optical spectroscopic program similar to that in Chapter 2, but carried out in the Lupus Clouds. A sample of previously selected YSOs is surveyed and spectral types are determined. The sample consists mostly of cooler, late-type M stars (90%). According to theoretical evolutionary models overlaid on H-R diagrams constructed for the sample, the population is ∼2 Myr old, with a mean mass of only 0.2 $M_{\odot}$. The Hα emission line yields a distribution of mass accretion rates typical of T Tauri stars ($10^{-6} - 10^{-11} M_{\odot}$ yr^{-1}).

Chapter 4 – This chapter presents a complete sample of flux-limited *Spitzer* IRS mid-IR (5–35 μm) spectra of the young stellar population of Serpens, as studied in Chapter 2. The spectra are presented and classified. In agreement with the findings in Chapter 2, the background population is further characterized into background stars (due to spectral slope and silicate features in absorption), background galaxies (with redshifted PAH features) and a high ionization object of unknown nature. The bona fide YSOs amount to 115 objects, comprising embedded (class I, 18%) and disk (classes II and III, 82%) sources. Inner disk geometry is inferred from the flux ratio between 30 and 13 μm. The silicate features at 10 and 20 μm are strongly affected by the size of its emitting dust and therefore used as a proxy for dust size. A population of small dust is seen in the surface layers of the disks independent of inner disk geometry, or of a clustered or isolated environment surrounding the stars. Additionally, the results from Serpens are compared with those for the young population in the well-studied Taurus star-forming region and with the c2d IRS sample spread across the sky. The results for Serpens are similar to these two populations of different mean ages and environments. This result implies that the dust population in the surface of disks arises from an equilibrium between particle growth and fragmentation, independent of environment. This equilibrium is maintained for as long as the disks are optically thick at optical and infrared wavelengths.

Chapter 5 – The high ionization object discovered in Chapter 4, OL17, is further studied here. Complimentary spectra are obtained with the X-shooter instrument on the Very Large Telescope (VLT). The wide wavelength range of the X-shooter's three arms (UVB, VIS and NIR) covers several important emission lines that are used to determine the object's nature. Narrow emission lines, combined with low [N II]/Hα and [S II]/Hα line ratios, show that the object is a new very dusty planetary nebula.

Chapter 6 – This chapter presents the grain mineralogy of the dust in disk surfaces for four clusters for which complete IRS samples exist: the young Serpens and Taurus samples discussed in Chapter 4, as well as the Upper Scorpius and η Chamaeleontis clusters which probe the older bin of disk evolution. The data are analyzed with the same techniques, allowing direct comparison of results. A similar distribution of mean mass-averaged grain sizes (few μm) and crystallinity fractions ($\sim$10 – 20%) is observed for the four regions, despite different mean cluster ages and disk fractions. The wide spread in cluster ages ($\sim$1–8 Myr) and disk geometries, without concurrent evolution of the disk surface dust properties, points to a rapid change taking place ($\leq$1 Myr) and an equilibrium such that these properties are statistically the same until disk dissipation.

Chapter 7 – This chapter makes use of the stellar and disk characteristics derived in the previous chapters in the construction of SEDs for the young stars with disks in Serpens. The SEDs allow a correct separation between stellar and disk radiation. Taking into account the new distance of Serpens (415 pc), a younger age distribution is found for the cloud, concentrated in the 1 – 3 Myr range. The distribution of disk fractional luminosities of the Serpens population resembles that of the young Taurus, with most disks consistent with passively irradiated disks. In terms of geometry, no clear separation in fractional disk luminosities is found between the flared and flat disks around T Tauri stars as is the case for the disks around more massive Herbig Ae/Be stars. Furthermore, the mineralogy of the dust in the disk surfaces does not seem to directly correlate with either stellar or disk parameters for the large sample studied.

Each chapter ends with its conclusions, deduced from the data there presented. Overall the main conclusions from this thesis are:

- Serpens and Lupus are both young regions, with mean ages ∼1.5 − 3 Myr (considering the distance to Serpens to be 415 rather than 259 pc). While the distribution of ages is very similar, the distribution of masses is not. Serpens is composed of a few early G and mostly K- and M-type stars, with masses spreading between 0.2 and 1.2 $M_\odot$, with a mean value around 0.7 $M_\odot$. This distribution is very similar to that of the young stellar population of Taurus. Lupus, however, is almost entirely composed of very low-mass M-type stars, peaking at ∼0.2 $M_\odot$. This distribution is very similar to the young star-forming regions Chamaeleon I and IC 348. This difference in mass distribution suggests some small deviations of a possible universal IMF.
- For any given region, be it a young ∼1 Myr or an old 7–8 Myr cluster, the distribution of the dominant size of the dust in the surface layers of disks is statistically the same. This implies that, besides coagulation and growth, this dust is also a result of destructive collisional processes. An equilibrium of these two processes must be maintained for millions of years, as long as the disk in optically thick at optical/IR wavelengths, to explain the same distributions observed.
- The mineralogical composition of the dust is on average the same for all regions. A considerable level of crystallinity (∼10 − 20 %) must be established in the disk surface early in the disk evolution (≤1 Myr), reaching an equilibrium that is independent of what may be happening in the disk midplane, where planets may be forming.

1.7 Outlook

The work presented in this thesis adds and expands on a large effort in the last decade to characterize the low- and intermediate-mass young stellar populations in the solar neighborhood. The great mapping capabilities and sensitivity of *Spitzer*, enhanced by ground-based surveys from optical to the mm regime, have allowed a thorough census of the disk population within a few hundred pc from the Sun. These observations, combined with large modelling efforts, have been able to set several constraints on how disks evolve. However, due to a lack of sensitivity of past and current facilities, very little is known about more distant star-forming regions. Studying their properties is especially important considering the vastly different initial conditions for regions in distinct parts of the Galaxy. Furthermore, nearby galaxies such as the Magellanic Clouds probe a very low metallicity environment, and their disk population cannot currently be resolved in the same detail as has been done for nearby star-forming regions.

In the upcoming years, the launch of the *James Webb Space Telescope (JWST)* has the potential to change this picture. With a 6.5-meter primary mirror, the telescope will be sensitive to radiation from 0.6 to 27 μm. These two characteristics combined make this an exceptional telescope for a significant step forward in the study of star and planet formation. The sensitivity of *JWST*, in imaging and low- and medium-resolution spectroscopy, will allow observations of distant environments, like young clusters in the Magellanic Clouds, resolving individual star+disk systems. These very low-metallicity environments could have very strong effects on the disk lifetime and evolution, which in turn could connect with the observed higher likelihood of finding planets around high metallicity stars in the solar neighborhood.

Targeting the dust in the inner ~100 AU of YSOs at a distance of 50, 100, or 200 pc will imply angular sizes of $2''$, $1''$, or $0.5''$, respectively. Given these small angular sizes and their prominence in the near- to mid-IR, the imaging and spectroscopic analysis of protoplanetary disks is among the main science drivers of the *JWST*. In the near-IR, NIRCam will provide virtually diffraction-limited, broad- and narrow-band imaging in the wavelength range of 0.6 to 5 μm (PSF of about $\lesssim 0.1 - 2''$, FWHM). The use of a coronograph can further enhance the contrast for low surface brightness objects (such as disks or planets around their host stars). NIRSpec will allow medium resolution (R $\sim$ 2000-4000) spectroscopy in the 1–5 μm range in any of three modes that are all ideally suited for spatially resolving the spectral properties of the disks. First, the IFU mode will allow full continuous sampling for moderately extended objects over a $3'' \times 3''$ region at a pixel size of $0\farcs1$. Second, fixed slits (either $0\farcs1 \times 1\farcs9$ or $0\farcs2 \times 3\farcs3$) can be placed on compact or elongated targets. Third, the microshutter assembly can be used to obtain spectra of arbitrary regions by sampling a single or multiple targets by opening a series of connected or disconnected microshutters each spanning $0\farcs2 \times 0\farcs46$ on the sky. These modes thus allow a spatial sampling of the spectral properties of protoplanetary disks up to 5 μm with about ten resolution elements for a 1000 AU disk at 400 pc, and about five resolution elements for a 100 AU disk at 50 pc. In the mid-IR, MIRI covers the 5–29 μm wavelength range for spectroscopy ($R \sim 3000$). Four IFUs will sample the wavelength range using spatial pixels of $0\farcs18 \times 0\farcs19$ (at ~ 6 μm), $0\farcs28 \times 0\farcs19$ (at ~ 10 μm), $0\farcs39 \times 0\farcs24$ (at ~ 15 μm), and $0\farcs64 \times 0\farcs27$ (at ~ 23 μm). These spatial samplings were chosen to match the *JWST* PSF at each wavelength, and imply that disks with diameters of about $2''$ will still be resolved with about five $\sim 0\farcs4$ resolution elements at the central wavelength of MIRI. The number of effective resolution elements for both NIRSpec and MIRI may be further improved by up to a factor of ~2 using clever dithering strategies.

In addition, the Atacama Large Millimeter/submillimeter Array (ALMA), operating in the wavelength range from 0.3 to 3.6 mm at 0.01 to a few arcseconds resolution, has great potential for the study of protoplanetary disks. The combination of sensitivity, angular and spectral resolution allows ALMA to probe the cold gas and dust in protoplanetary disks across almost the entire disk, not just limited to the surface areas. Continuum and lines constrain many of the chemical and physical processes taking place in disks, as well as disk mass and luminosity that are highly uncertain without (sub-)mm points. ALMA will be able to spatially resolve the inner and outer parts of the closest disks, directly imaging the critical 3 – 30 AU regions of the disk where planets are thought to form, thus complementing mid-IR studies of the innermost (∼1 AU) disk.

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