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## **The first steps of planet formation : studying grain growth with millimetre interferometers**

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# Chapter 1

## Introduction

The Milky Way contains about 200 billion stars, of which the Sun is only one unremarkable example. We live on Earth, one of eight planets<sup>1</sup> revolving around the Sun in a more or less flat plane. It was suggested a long time ago that our Sun is not the only star with planets (Epicurus 300 B.C.; Bruno 1584). However, it was only at the beginning of the last decade of the twentieth century that a planet outside of our solar system was found (Bailes et al. 1991). This planet is orbiting a neutron star, the remnant of a massive star whose life ended in a supernova, and probably this planet had a very different formation history than our own Earth. In 1995, a planet was discovered around a star more similar to our Sun, 51 Peg (Mayor & Queloz 1995). Since then, more than 300 planets outside our solar system, so-called exoplanets, have been found.

Planets are generally accepted to be the by-products of stars, which are formed when interstellar clouds of gas and dust collapse under the forces of gravity. The details of this formation process are still largely unknown and this thesis is part of the world-wide effort to unravel the secrets of star and planet formation.

### 1.1 Star formation

Between smaller and larger groups of stars, there are clouds of gas and dust permeating the Galaxy, so-called Giant Molecular Clouds (GMCs). These clouds can be stable over periods of millions upon millions of years, with gas pressure and turbulence working against the gravity that might otherwise pull the clouds together. Magnetic fields may also alter the dynamical state of a molecular cloud sufficiently to prevent gravitationally unstable regions from collapsing (Shu et al. 1987). At some point in time, however, these clouds will become unstable and

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<sup>1</sup>Pluto was demoted from a planet to a dwarf planet (e.g., Binzel 2006). The eight planets of the solar system are, with increasing distance from the Sun: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune.

start to collapse under their own gravity. This may happen when, for instance, a supernova goes off nearby and sends a pressure wave through the cloud. This may cause the neutral particles in the cloud to decouple sufficiently from the charged particles (ambipolar diffusion, e.g., Mouschovias 1977), so that the support from magnetic fields can be overcome. While hydrodynamical turbulence can perhaps prevent global collapse, it can never completely prevent local collapse (Klessen et al. 2000) and the cloud will start to fragment. Locally within the cloud, the forces of gravity become larger and overcome the gas pressure. Several clumps of material will start to collapse and one GMC may eventually harbour hundreds or even thousands of dark cores, several of which may eventually form stars and planets.

With pressure at least temporarily overcome, the dark core will continue to collapse. However, in every cloud and core a net quantity of angular momentum is present which prevents the core from collapsing spherically symmetrically and a flattened structure must form. Material moves inwards through the structure under the force of gravity while angular momentum moves outwards and thus a disc-like structure with a bulge in the centre is naturally formed. As more and more material falls onto the disc and the central protostar, the system can no longer get rid of the excess angular momentum by moving it outward through the disc. Consequently, possibly in conjunction with the magnetic field present in the disc, jets are formed close to the central structure. These jets eject material from either pole in the system, forming outflow cavities in the surrounding envelope in the process. Thus, while in the outer part of the system material from the envelope is still raining down on the disc, in the centre some of the material is ejected and returned to the interstellar medium. In this phase, the system is an embedded young stellar object, class I in the Lada classification (Lada & Wilking 1984, and below). A schematic picture of a class I object is shown in the top panel of Fig. 1.1.

After several hundred thousand years, the envelope is dispersed and we are left with a young stellar object, consisting of a protostar surrounded by a protoplanetary disc. The temperature in the core of the central object is not yet high enough for the fusion of atomic hydrogen and it derives most of its luminosity from conversion of gravitational potential energy into kinetic energy and hence heat. The disc around it has initially a consistency similar to that of the interstellar medium, implying that some 99% of the mass is gas with the remaining 1% being dust. The dust grains are silicate- and carbon-based and in the colder regions they are covered with icy layers of, e.g., water, carbon dioxide, and methane. They have sizes in the range of  $0.003 \mu\text{m}$  up to  $\sim 0.1 \mu\text{m}$ . It is from these tiny grains that

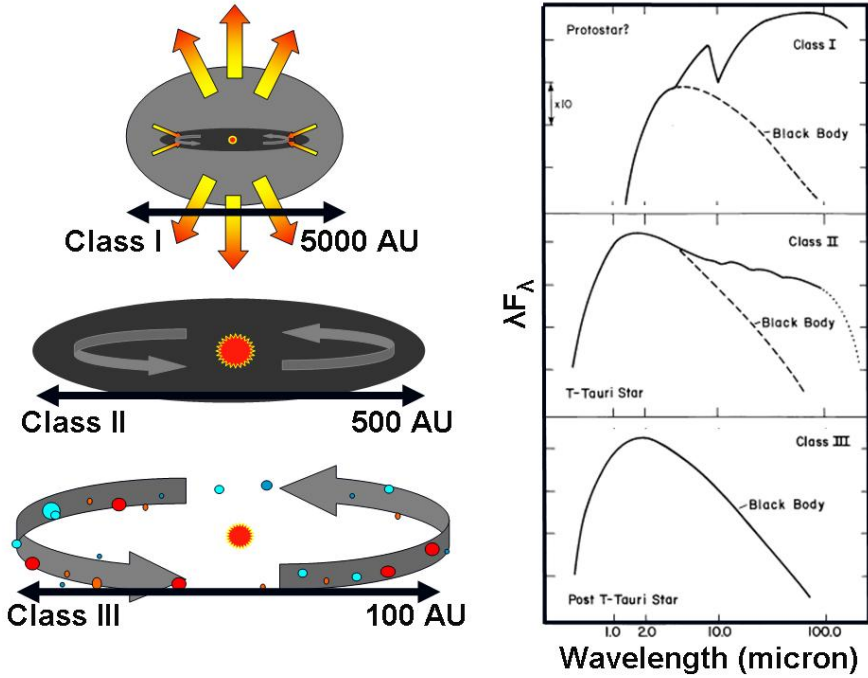


Figure 1.1: An overview of the three so-called Lada classes of star formation (Lada & Wilking 1984). On the left, schematic representations of the geometry of the system are given, in which the protostar, the circumstellar disc, the envelope, and eventually the pre-planetary system can be distinguished. On the right, characteristic spectral energy distributions are shown (see Sect. 1.3.1).

eventually planets are formed. The evolution of a low-mass young stellar object is depicted by a cartoon in Fig. 1.1.

This thesis is mainly concerned with these circumstellar discs in young stellar objects. Using observations and computational models we will address the following questions. When does the disc form? How large is it? When, how fast, and where in the disc do grains grow? Can we test the evolution of envelope, disc, and stellar mass shown in Fig. 1.2 (based on Hueso & Guillot 2005)?

A natural way to describe the structure of a circumstellar disc is through the regions that can be probed with different kinds of observations. Light is very efficiently scattered by small particles and thus we can see circumstellar discs out to large distances from the star through optical and near-infrared scattered light.

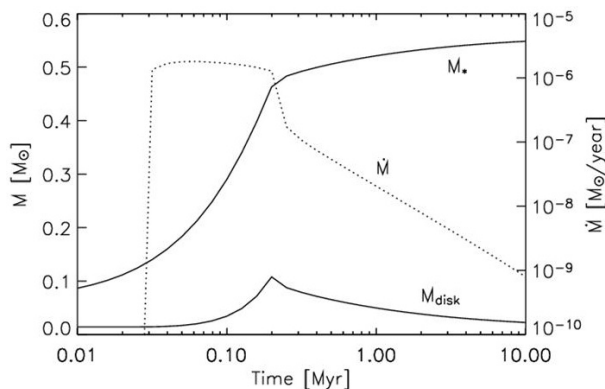


Figure 1.2: Schematic picture of the mass evolution of the disc and the central star (based on Hueso & Guillot 2005). The dotted line shows how the stellar accretion rate changes over time.

However, these observations only graze the disc surface. Mid-infrared images and spectra probe the atmosphere of the disc, but only the warmer regions. These regions may conveniently be called the inner disc, typically located within a few AU from the young star. The outer disc, then, is best studied at (sub)millimetre and centimetre wavelengths. At these wavelengths, most of the emission is optically thin and the bulk of the disc matter can be probed. Finally, a region that cannot be observed directly but is inferred from disc modelling is the so-called “dead zone” in the mid-plane of the inner disc. This is a somewhat quiescent region with less turbulence than elsewhere in the disc. However, it is important in the sense that planetesimals may actually be formed near or in the “dead zone,” as we will see below. A schematic picture of a protoplanetary disc with the most important regions is shown in Fig. 1.3.

## 1.2 Grain growth and planet formation

The formation of kilometre-sized planetesimals from what originally are submicron-sized dust grains was studied in the classic work by Weidenschilling (1980) and a comprehensive recent review can be found in Youdin & Johansen (2008). The most important processes involved are described in this Section and summarised in Fig. 1.4.

The first step in the long road from interstellar-sized grains to planets is when

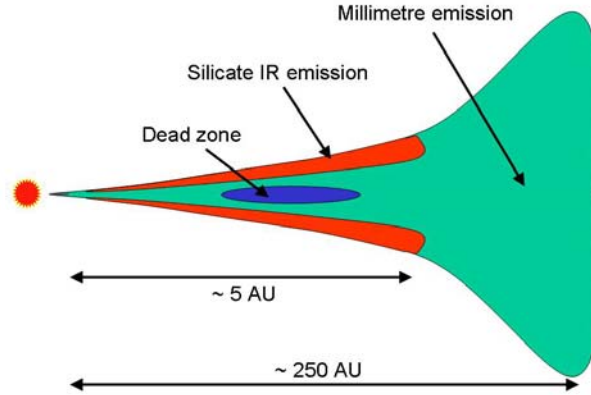


Figure 1.3: A schematic picture of a protoplanetary disc. Indicated are the outer disc, the atmosphere of the inner disc, and the low-turbulence “dead zone.” The mid-infrared emission, including the silicate features around  $10$  and  $20\ \mu\text{m}$ , originates in the atmosphere of the inner disc, while (sub)mm observations basically probe the entire disc. Picture based on a presentation by Carsten Dominik.

grains less than a micron in size grow to sizes of a few microns. The particles will behave in the ensuing gas as smoke in the air: they move in Brownian motion under the influence of the gas molecules and will occasionally collide with each other. Upon collision, two grains will usually stick at the very low relative velocities of a few  $\text{cm s}^{-1}$  produced by Brownian motion (Dominik & Tielens 1997; Paszun & Dominik 2006; Blum & Wurm 2008). Models and laboratory experiments show that grain growth from interstellar, submicron sizes to particles of several milli- or centimetres in size is straightforward and fast.

Once the particles have reached sizes in the order of centimetres, they become more likely to fragment upon collision (Blum & Wurm 2000). However, it turns out that the largest particles will still grow if collisional charging and electrostatic reaccrusion (e.g., Blum 2004; Blum & Wurm 2008) or reaccrusion by gas flow (e.g., Wurm et al. 2001; Sekiya & Takeda 2003) are taken into account. In this way the dust grains may grow to decimetres in size.

The growth of objects larger than decimetres in size can as yet not be studied in the laboratory. Furthermore, at these large sizes, the interaction of the particles with the surrounding disc becomes more important and the problem is at-

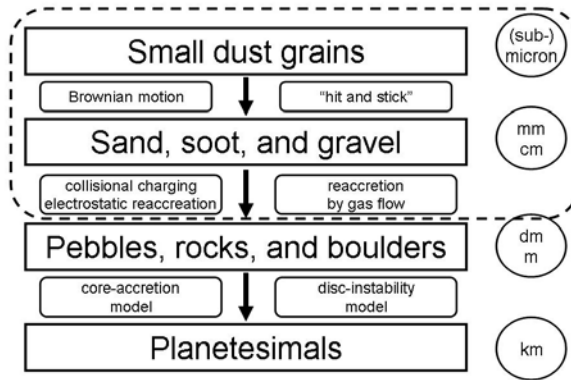


Figure 1.4: An overview of the most important processes governing the growth from (sub)micron-sized dust grains to millimetre- and centimetre-sized pebbles, decimetre- and metre-sized boulders, and finally to planetesimals. The dashed line encompasses the grain sizes which are observationally studied in this thesis. Picture based on a presentation by Jürgen Blum.

tacked with numerical models, in which a large part of, or even the whole disc are taken into account. Johansen et al. (2007) formed planetesimals and dwarf planets through gravitational collapse in the mid-plane of turbulent discs. However, they required metre-sized bodies as a starting point for the scenario. Lyra et al. (2008a) started with grains of 1 up to 100 cm and found that these could grow to objects the size of Mars within several thousand years, when trapped in waves at the edge of the quiescent, almost turbulence-free “dead zone” in the centre of protoplanetary discs. A rather more complete picture was subsequently drawn by Brauer et al. (2008a,b), who started with microphysics including Brownian motion, differential settling, and turbulent coagulation (Brauer et al. 2008a) and subsequently formed kilometre-sized bodies near the “snow line” in a few thousand years (Brauer et al. 2008b).

Two competing models exist for the formation of gas giants such as Jupiter and Saturn in our own solar system and most of the planets orbiting other stars found so far. In the core-accretion model (e.g., Safronov & Zvjagina 1969; Goldreich & Ward 1973; Hayashi et al. 1985; Pollack et al. 1996), a heavy-element core is built by the accretion of planetesimals, much as described in the previous paragraph.

As the core becomes more massive, its ability to accrete gas from the surrounding disc increases. At some point the core may become massive enough for rapid accretion of gas and a gas giant is formed. In the disc-instability scenario (e.g., Kuiper 1951; Cameron 1978; Boss 1997), a sufficiently massive disc will fragment into dense cores. These clumps can contract to form gas giants much in the same way as proto-stellar systems are formed from their parental cloud (see previous Section). Though some problems still exist for both scenarios, it is interesting to note that some 90% of the exoplanets found so far can be reasonably well explained with the core-accretion model, while the remaining 10% could have been formed through the disc-instability model (Matsuo et al. 2007).

It thus seems that the processes leading from small grains to large planets are fairly well understood. However, all models will eventually have to be tested against experiments, or in the case of astronomy, observations. The observations of young stellar objects are the subject of the following Section.

## 1.3 Observing the evolution of young stellar objects

### 1.3.1 A classification of young stellar objects

Lada & Wilking (1984) introduced an empirical classification of young stellar objects, based on their spectral energy distributions (SEDs) in the infrared (see Fig. 1.1). The SEDs of class I objects are completely dominated by emission from the circumstellar envelope, which entirely obscures the central star. In class II objects, the envelope has been dispersed and the central star has become visible. A strong excess over the photosphere of the star is still present, though, due to the warm gas in the circumstellar disc. Over time, also the gaseous disc is lost due to accretion processes and photo-evaporation and what is left is an SED which is dominated by the central star and only has a small excess due to the dust in a debris disc. Though this classification has proved extremely useful, it is not foolproof. For example, a system without an envelope that is viewed edge-on may produce a class I SED. Van Kempen et al. (2009) found for a sample of more than 40 young stellar objects in Ophiuchus that were at some point classified as class I objects, that less than half were indeed genuine class I as originally defined in the Lada classification. Different observables have been proposed to determine the evolutionary stage of a young stellar object (e.g., Robitaille et al. 2006) and Crapsi et al. (2008) concluded that one of the best diagnostics to determine whether an object is embedded or not is by comparing the single-dish flux to the interferometric flux at (sub)millimetre wavelengths (see also below).

### 1.3.2 Observing the growth from submicron to micron sizes with the 10- $\mu\text{m}$ silicate feature

Since new stars are formed from the interstellar medium, the dust composition is initially also the same as that of the interstellar medium. More particularly, the initial dust size distribution is that of the interstellar medium, with a typical size of  $\sim 0.1 \mu\text{m}$ . Due to coagulation, these dust grains will grow, first to sizes of a few  $\mu\text{m}$  and later to larger sizes, and the high temperature locally in the inner disc will anneal the mostly amorphous grains to more crystalline structures. These very first steps of grain growth can be observed in the infrared, most notably using the silicate features around 10 and 20  $\mu\text{m}$ . These features can be observed from the ground as was done by, e.g., Meeus et al. (2001) and Przygodda et al. (2003). Over the last several years, a large number of interferometric observations have been obtained in the infrared, in particular using the MIDI instrument (Leinert et al. 2003) operating on the Very Large Telescope (Glindemann et al. 2000) around 10  $\mu\text{m}$ . Ground-breaking results were obtained by van Boekel et al. (2004), who used MIDI to observe the Herbig-Ae star HD 144432. The observations clearly showed the presence of more crystalline material in the inner disc, whereas the dust in the outer disc was predominantly amorphous. Furthermore, both the change from amorphous to more crystalline grains as well as the growth of submicron sizes to sizes of several microns have been observed by the Infrared Space Observatory (ISO, Malfait et al. 1998; van Boekel et al. 2005). More recently, the Spitzer Space Telescope was used to observe the infrared spectra of many more, also considerably weaker young stellar objects (e.g., Furlan et al. 2006; Kessler-Silacci et al. 2006). A large range of 10- $\mu\text{m}$  features was observed, ranging from strong, peaked features to weak, flat-topped features. Comparison with synthetic spectra of small grains showed that the different features can be quite naturally explained with grain growth: the 10- $\mu\text{m}$  feature is strong and peaked for interstellar grains of about 0.1  $\mu\text{m}$  in size, whereas the feature is largely gone by the time the grains have reached sizes of  $\sim 6 \mu\text{m}$  (see Fig. 1.5). However, processes other than grain growth have been proposed to explain the evolution of the 10- $\mu\text{m}$  feature. For example, if large grains settle to the mid-plane, they no longer contribute to the 10- $\mu\text{m}$  feature, which would thus over time attain the stronger and more peaked shape associated with the smallest grains (Dullemond & Dominik 2008).

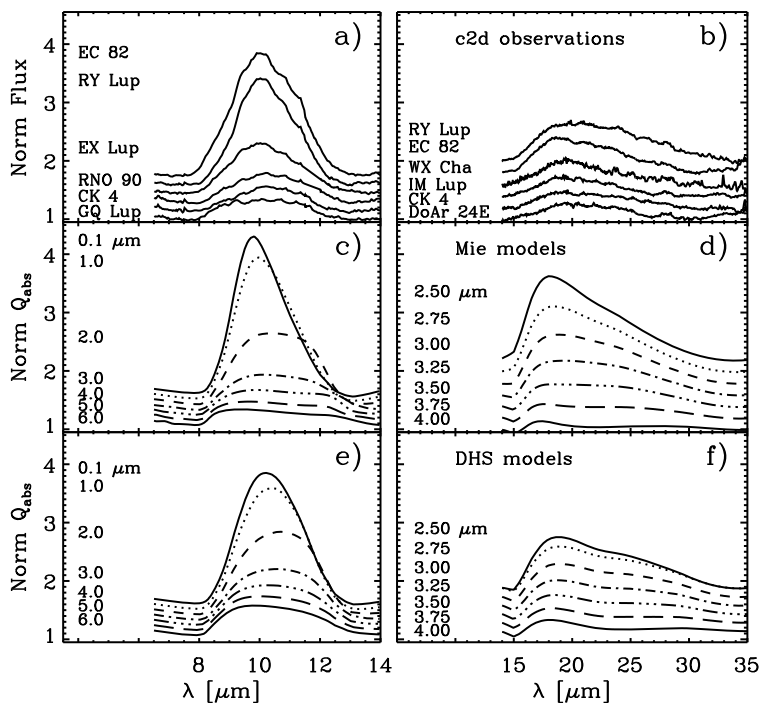


Figure 1.5: The evolution of the 10- and 20- $\mu\text{m}$  silicate features. *Upper panel:* observations from the Spitzer “c2d” Legacy program. *Middle panel:* synthetic spectra created using filled homogeneous spheres. *Bottom panel:* synthetic spectra created using a distribution of hollow spheres (from Kessler-Silacci et al. 2006).

### 1.3.3 Observing the growth from gravel to boulders at long wavelengths

Growth to larger sizes can only be observed at longer wavelengths and seminal work on this was done by Beckwith et al. (1990) and Beckwith & Sargent (1991). They observed a large number of young stellar objects at submillimetre (submm) and millimetre (mm) wavelengths with single-dish telescopes and determined the (sub)mm slope of the spectral energy distribution. They found slopes  $\alpha \approx 2$ , where  $F_\nu \propto \nu^\alpha$ . The interstellar medium has values around  $\alpha = 3.7$  (cf. Draine 2006) and the shallower mm slope found for the dust in circumstellar discs was interpreted as grain growth. Indeed, numerical models of dusty discs predict that the (sub)mm slope becomes shallower when larger grains are included (e.g.,

Dullemond & Dominik 2004a). However, the observed shallow slopes can also be caused by small, optically thick discs. Furthermore, there may be contributions from a (remnant) circumstellar envelope. It is therefore necessary to observe these young systems with interferometers to filter out extended emission and resolve the discs spatially in order to unambiguously attribute the shallow spectral slope to grain growth. This has been done in recent years (e.g., Natta et al. 2004; Rodmann et al. 2006; Andrews & Williams 2007) and several dozen young stellar objects with dust of at least mm sizes have been found. Even larger grains, or pebbles, can only be observed at centimetre wavelengths. However, the detection of thermal emission from dust is notoriously difficult at such long wavelengths where the emission is tailing off and other emission mechanisms such as winds or chromospheric activity may also contribute. Wilner et al. (2005) used the Very Large Array to resolve and monitor the pre-main-sequence star TW Hya and found decimetre-sized pebbles in the disc.

### 1.4 Millimetre interferometers

As explained above, the first steps of planet formation are well observed in the infrared and at (sub)mm and cm wavelengths. Observations have shown that dust is processed in the discs around young stars. The next step is to find out where exactly grain processing or growth is taking place. This requires high-spatial-resolution observations, with which the systems can be spatially resolved. The highest spatial resolution is obtained using the telescopes with the largest dishes or mirrors. However, there are physical limitations to how large a single telescope can be. Higher resolution can then be obtained using the technique of interferometry. With interferometry, an object is simultaneously observed with two (or more) telescopes and the signals of the two telescopes are allowed to interfere, either directly or after digitisation. The information that can be obtained in this way has the same spatial resolution as if one were using a telescope with a diameter as large as the distance between the two telescopes.

Interferometric observations of young stellar objects at mm and cm wavelengths are very useful, because they can resolve the circumstellar discs. As long as a disc is unresolved, it is possible that the spectral slope is affected by a very small, optically thick disc. Only if the emission at (sub)mm wavelengths is optically thin, the flux is a rather direct measure of the disc's mass. Furthermore, (sub)mm interferometry allows us to separate disc emission from envelope emission, as is demonstrated in Fig. 1.6 (from Jørgensen et al. 2005). This Figure shows the flux as a function of baseline length for NGC 1333-IRAS 2. Shorter

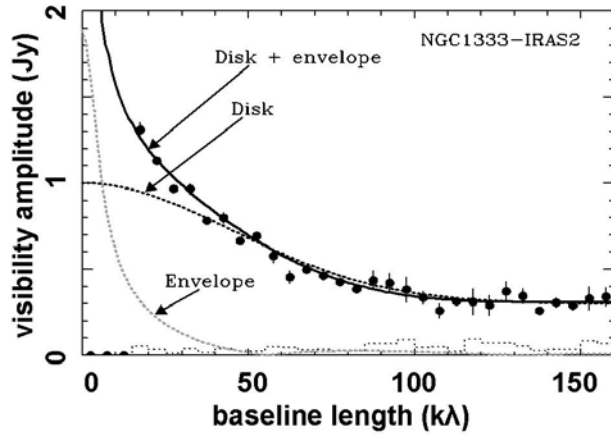


Figure 1.6: The flux as a function of baseline for the embedded young stellar object NGC 1333-IRAS 2, from Jørgensen et al. (2005). Overplotted are the flux due to the circumstellar envelope, constrained by single-dish SCUBA observations (Jørgensen et al. 2002), and the flux due to the resolved circumstellar disc.

baselines probe larger scales and the flux drops towards longer baselines. This can be explained as follows. On the smallest interferometer baselines the telescope has a large beam and the detected flux is that of all the matter included in the beam, in this case the circumstellar disc and the envelope. On the longer baselines the telescope is sensitive to smaller scales and only the flux of the disc is detected. In this way the emission of the disc and that of the envelope can be neatly separated.

## 1.5 This thesis

This thesis is largely aimed at sources in the southern sky and the only mm and cm interferometer that can currently observe the southern-most sources is the Australia Telescope Compact Array (ATCA). We used the ATCA to observe T-Tauri stars in the southern star-forming regions Lupus, Chamaeleon, and Corona Australis at 3 mm and a number of sources at 7 mm, 3.5, and 6.3 cm. The sources in Lupus and Corona Australis were also observed with the Submillimeter Array (SMA) at 1 mm. The SMA is located on Mauna Kea on Hawaii and can still reach several of the star-forming regions in the southern hemisphere. It is also used

to observe two embedded, class I, objects in the  $\rho$  Ophiuchi star-forming region. Finally, the more northern Combined Array for Research in Millimeter-wave Astronomy (CARMA) and the Very Large Array (VLA) were used to observe a number of class II objects in Serpens at 1 and 3 mm (CARMA) and at 7 mm, 1.3, 3.6, and 6.2 cm (VLA).

In Chapter 2, we present SMA observations of two embedded sources with young discs. These two young stellar objects were previously classified as class I in the Lada classification. A survey of bright T-Tauri stars in the southern constellations Lupus and Chamaeleon was carried out using the ATCA at 3 mm, the results of which are presented in Chapter 3. The Lupus sources were subsequently observed with the SMA at 1 mm. The results of Chapter 3 were followed up with a larger survey of T-Tauri stars, using the SMA, ATCA, CARMA, and VLA interferometers and the Spitzer Space Telescope in Chapter 4. Finally, in Chapter 5, we show ATCA monitoring observations at centimetre wavelengths of three sources from the sample presented in Chapter 3, allowing us to constrain the physical processes responsible for the emission. RU Lup and WW Cha were the brightest sources in that sample and had fairly shallow millimetre slopes, indicating the presence of large grains.

The main conclusions of this thesis are the following.

- Interferometric observations can separate the discs and envelopes of young stellar objects at (sub)mm wavelengths as well as the objects from their environment. The masses of the envelopes and discs of the class I objects IRS 63 and Elias 29 have been determined, giving ratios of  $M_{\text{env}}/M_{\text{disc}}$  of 0.2 for IRS 63 and 6 for Elias 29. High-spatial-resolution observations of the motion of the molecular gas in the discs are used to determine the masses of the central objects for the first time,  $0.37 \pm 0.13 M_{\odot}$  for IRS 63 and  $2.5 \pm 0.6 M_{\odot}$  for Elias 29 for a fiducial inclination of  $30^{\circ}$ , indicating that the central stars have practically reached their final mass (Chapter 2).
- A total of 26 southern discs are detected at mm wavelengths with the SMA, ATCA, and CARMA. Several of these sources are resolved, indicating that the emission is optically thin at these wavelengths. The (sub)mm slope  $\alpha$  is determined and found to cluster around 3, where  $F_{\nu} \propto \nu^{\alpha}$ , implying that millimetre-sized grains must be common in the discs of T-Tauri stars (Chapters 3 and 4).
- A correlation is found between the strength of the  $10\text{-}\mu\text{m}$  silicate features and the mm slopes. As the  $10\text{-}\mu\text{m}$  feature probes the surface layers of the inner disc and the mm slope probes the outer disc, this means that

grain growth must be fast throughout the disc. The sources are more or less grouped by star-forming region in the 10- $\mu\text{m}$ -feature versus mm-slope diagram. Synthetic spectra were created using the radiative-transfer tool RADMC and they show that this grouping can be explained if one assumes that grain growth has progressed further in some of the star-forming regions than in others. However, it may also point to a chemical variation between the different star-forming regions (Chapter 4).

- RU Lup and CS Cha are found to have dust emission up to 7 mm and WW Cha up to 1.6 cm, indicating the presence of pebble-sized grains. Other mechanisms are responsible for the emission at longer wavelengths for RU Lup and WW Cha (Chapter 5).

The study of young stellar objects with (sub)mm and cm interferometers is a relatively young and very exciting field in which many interesting results have been obtained in the past several years. The future of this field is extremely bright. Firstly, the upgrade of the ATCA with the Compact Array Broadband Backend (CABB), which will increase the bandwidth with a factor of 16, is practically finished. This will make surveys of young stellar objects at mm and cm wavelengths in the southern sky much more feasible, which in turn will allow us to obtain the necessary statistics to draw firmer and stricter conclusions. Likewise, the upgrade of the VLA to form the Expanded Very Large Array (EVLA) will increase the continuum sensitivity by a factor of 5 to 20, giving a point-source sensitivity better than 1  $\mu\text{Jy}$  between 7 mm and 15 cm and accessing the northern skies to similar surveys. The e-MERLIN telescope array, which will provide radio imaging, spectroscopy, and polarimetry with 10-150 milliarcsecond resolution and  $\mu\text{Jy}$  sensitivity at cm wavelengths, is also nearing completion. Next, the Atacama Large Millimeter/submillimeter Array (ALMA) is expected to start operations in a few years time, opening up the southern skies to wavelengths between 0.35 and 3.6 millimeters. The unprecedented spatial resolution at these wavelengths will make it possible to study the growth of grains to pebbles as a function of location in the disc. Finally, the Square Kilometre Array (SKA) is being planned. Construction of the first elements of the SKA is expected to start in 2012, with completion of the array by 2020. The SKA will allow observations at about 1 cm and longer at milliarcsecond resolutions to find rocks and boulders in protoplanetary discs.

