Chapter 1

Introduction

1.1 "The chaotic material of future suns"

Although galaxies may be the building blocks of the universe, the stars that form, evolve, and die within them make galaxies into the complex and beautiful systems they are. It has been long established that stars form when clouds of gas and dust collapse under their own gravity, but many of the details remain uncertain. For example, the distribution of stellar masses formed in different environments, or the efficiency with which interstellar material is transformed into stars, are major questions determining the appearance and evolution of a galaxy. Before we can hope to solve any of these issues, we need to understand how the formation of a single star proceeds. The interaction of infalling gas with magnetic fields and the powerful wind emanating from young stars play central roles. The process by which the remnants of the progenitor cloud core are eventually collected into a new planetary system is particularly important and fundamental, since it directly influences our understanding of the formation of our own Solar System, and of the recently detected planetary systems around other stars (Mayor & Queloz 1995; Marcy & Butler 1996).

This thesis investigates the earliest stages of the formation of Sun-like stars, using new and improved observational facilities at (sub)millimeter wavelengths. The structure and evolution of the envelopes in which the stars are embedded and from which they may still be accreting mass is addressed, and the presence and evolution of circumstellar disks —the progenitors of planetary systems— is investigated. The aims and adopted strategies are discussed in more detail in §1.3, together with a short outline of the thesis. §1.4 draws conclusions from the results of the individual chapters. In the following, we first discuss the current state of knowledge of the star-formation process (§§1.1.1 and 1.1.2), along with the potential of molecular lines and dust continuum emission to probe the physics and chemistry of the protostellar environment (§1.2).

1.1.1 Star-forming environments

For centuries, it has been realized that interstellar gas clouds are the cradle of stars. In 1789 the great astronomer Herschel described the Orion Nebula as "*the chaotic material of future suns*" (Glyn Jones 1968). The modern era of star-formation theory began with the formulation by Jeans in 1902 of the instability conditions of a self-gravitating system (Jeans 1928). In 1955 Bok hypothesized that the dark clouds now called Bok globules are the sites of active star formation (Bok 1955). Until the advent of infrared and millimeter astronomy in the late 1970's, however, the observer's view of star formation was limited to the relatively late T Tauri and pre–main-sequence stages when the young star is no longer obscured by the large amounts of gas and dust of its progenitor cloud core. Only mystifying glimpses of the embedded phases of the star-forming process were offered by the so-called Herbig-Haro objects (Haro 1949; Herbig 1950, 1951), which by 1975 were understood to be parcels of gas shocked by the powerful wind or jet emanating from very young stars (Schwartz 1975).

A great leap forward in our understanding of the structure and composition of the dense interstellar medium and the process of star formation was initiated by the availability of infrared and millimeter instrumentation. Excellent reviews of the wide body of observational material gathered over the last two decades on these subjects can be found in the conference proceedings edited by Levy & Lunine (1993), Lada & Kylafis (1993), and Reipurth & Bertout (1997). The different environments in which stars form appear to be characterized by two extremes. In dark cloud complexes like Taurus–Auriga, predominantly low-mass ($\lesssim 3\ M_\odot$) stars form at a low rate and in relative isolation from each other. In sharp contrast, more massive giant molecular clouds like the Orion Molecular Cloud collapse and fragment to form clusters of a thousand stars or more over the course of a few Myr (Hillenbrand 1997). A few of the newly-formed stars are so massive ($\gtrsim 10\ M_\odot$) that they emit copious amounts of ultraviolet radiation which destroys the remaining cloud material, and which may cut short further mass accretion of the surrounding stars, as well as the evolution of their circumstellar envelopes and disks. It is, however, unclear to what extent star formation is indeed bimodal, or whether the Taurus and Orion regions are simply extremes in a distribution of star formation density. Both regions are by far the closest and best studied regions of their kind, which may influence our perception significantly. Other regions like ρ Ophiuchi and Serpens also show high star formation densities without the O-star content of Orion. It is equally unknown to what extent the initial mass function (IMF) differs between various star-forming environments, and whether the generic field IMF is a superposition of the IMFs of such different environments. The properties of the molecular cloud from which the Sun was formed are ill constrained as well.

This thesis focuses on two star-forming regions. The Taurus–Auriga region is the prototypical site of low-mass, isolated star formation. It offers an excellent opportunity to investigate the star formation process in absence of any disturbance, while its close proximity ensures good spatial resolution. The Serpens molecular cloud extends the parameter range to one of the densest regions of star formation (Eiroa & Casali 1992), and to intermediate mass (1–4 $M_\odot$) stars in the earliest stages of their formation.

1.1.2 The isolated formation of a low-mass star

Based on infrared and millimeter observations gathered since the early 1980's, a nearly complete picture has emerged of the formation of an isolated low-mass star (Shu, Adams, & Lizano 1987, 1993). The different stages are schematically depicted in Fig. 1.1., and roughly correspond to the different classes of spectral energy distributions (SEDs) of young stellar objects (YSOs) identified by Lada (1987) and André, Ward-Thompson, & Barsony (1993).

(*a*) The formation of a star commences with the growth of condensations in molecular clouds. Interstellar clouds are supported by turbulent motions and magnetic fields of 10–50 μG (Crutcher et al. 1993; Heiles et al. 1993). Only charged particles, which make up a small fraction of the total amount of material, are coupled to the magnetic field

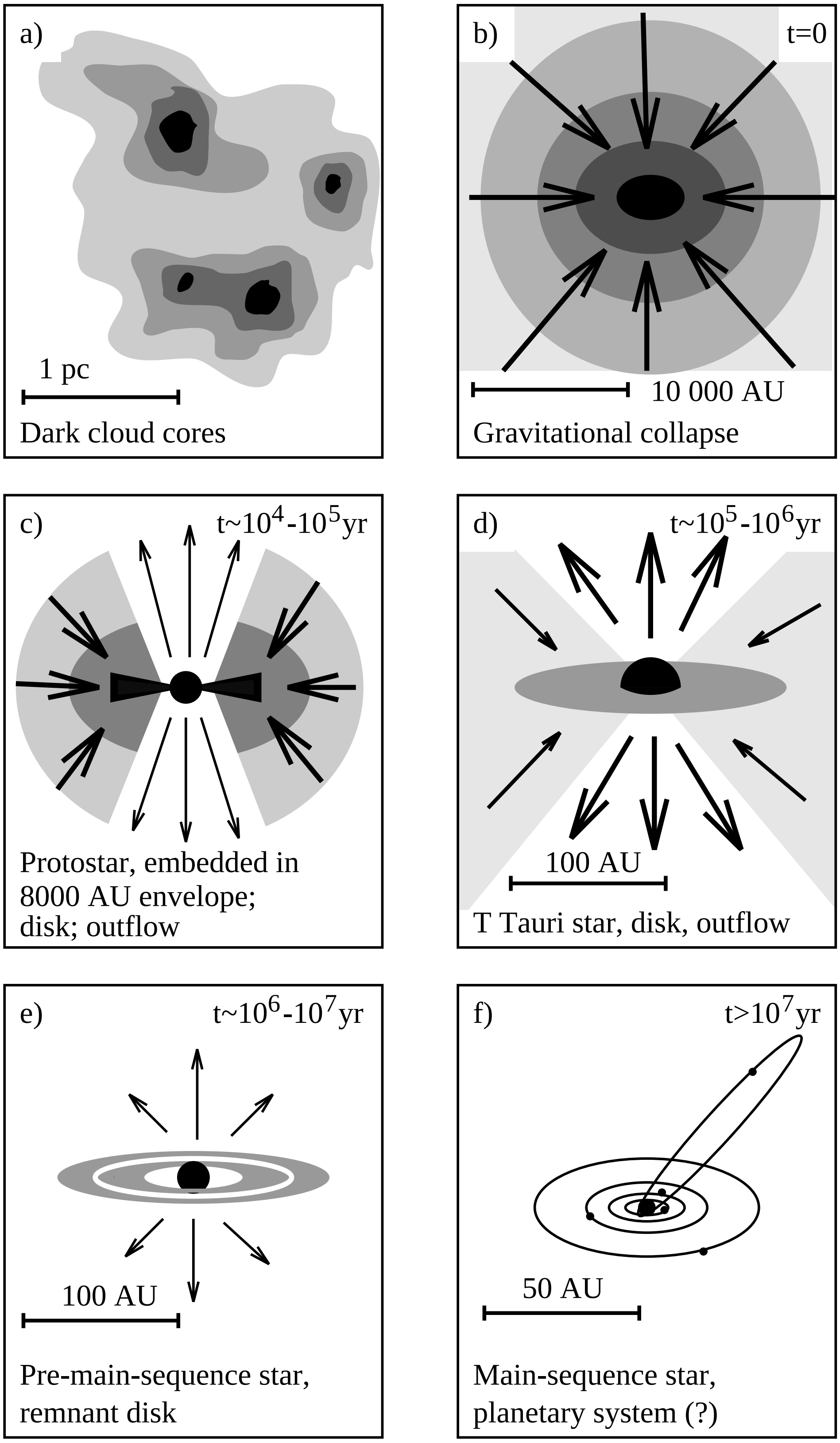

Fig. 1.1. *Schematic overview of the formation of a low-mass star (after Shu et al. 1987).*

lines. The neutrals will slowly slip past the field lines — a process known as ambipolar diffusion — so that a strongly centrally concentrated cloud core will form on a time scale of $\sim 10^6$ yr (Nakano 1979; Lizano & Shu 1989; Fiedler & Mouschovias 1992, 1993; Basu & Mouschovias 1994). Theoretical work predicts a density configuration that tends to that of a singular isothermal sphere, $\rho \propto r^{-2}$. Observations of various dark clouds reveal cores with slightly elongated shapes (Myers et al. 1991). The central density distribution in cores without embedded stars is found to be flatter than in cores with an embedded star, where the density closely follows the predicted r^{-2} distribution (Ward-Thompson et al. 1994; Motte, André, & Neri 1998).

(*b*) When the density at the center of the core exceeds a critical value, it becomes dynamically unstable and starts to collapse (Shu 1977; Li & Shu 1996b). The information of the collapse of the central region travels outward with the local speed of sound, and exterior layers begin to fall in. This is known as *inside-out* collapse. Theoretical models of, e.g., Cassen & Moosman (1981), Terebey, Shu, & Cassen (1984), Galli & Shu (1993a), Boss (1993), and Li & Shu (1997) describe the structure of the collapsing envelope in various levels of detail, including the effects of rotation and magnetic fields. At the center of the envelope a hydrostatic core forms, growing in mass as material continues to fall in. This purely infalling stage, before the onset of an outflow (see below), is the still unobserved holy grail of star-formation studies.

(*c*) The subsequent evolutionary phase is characterized by a protostar, deeply embedded in an infalling envelope and possibly surrounded by a disk. A striking phenomenon during this phase is that of the bipolar outflow driven by almost all embedded YSOs. Although initially puzzling (cf. Snell, Loren, & Plambeck 1980), outflows are now understood to be intimately associated with the interaction of an accretion disk and a stellar magnetic field, and to be an essential means of carrying away excess angular momentum from the accreting protostar. Two SED classes are assigned to this embedded phase. During the first few$\times 10^4$ yr the object is surrounded by sufficient gas and dust to obscure it at wavelengths shorter than ~ 100 μm. The SEDs of these class 0 sources (André et al. 1993) are well described by a single blackbody of ~ 30 K. A class 0 object can be properly called a protostar, since its envelope mass exceeds that of the star itself, and it derives most of its luminosity from accretion.

During the subsequent few$\times 10^5$ yr, the envelope material either accretes onto the central star, or is being swept away by the outflow. The object, now characterized by a class I SED, can be observed up to the near-infrared, but is still obscured at visible wavelengths. The outflows of class I sources are generally found to be less powerful than during the class 0 stage (Saraceno et al. 1996). This view may be slightly biased, however, since most class 0 source have been found by their outflows, while class I objects are identified by the infrared emission from their envelopes. Sensitive (sub)millimeter bolometer arrays like SCUBA and SHARC hold much promise for a better characterization of the full extent of the embedded phase.

Observationally, the division of the embedded phase into separate SED classes is sound, although different source orientations may blur the classification of transitional objects. In terms of physical processes, the division may be somewhat artificial. The whole embedded phase is characterized by an envelope, which is being depleted by the competing processes of ongoing infall and entrainment in the bipolar outflow.

(*d*) During the subsequent T Tauri phase, it is the evolution of the circumstellar disk which takes center stage. Having lost virtually all envelope material, the star is optically visible, and its SED (class II) is characterized by the infrared emission of the disk, and the optical and ultraviolet emission associated with accretion. At least half of T Tauri stars are surrounded by a disk massive enough to form a planetary system (Beckwith et al. 1990). The gas content of these disks are probed by a variety of tracers (e.g., Koerner, Chandler, & Sargent 1995); Mannings & Sargent 1997).

(*e*) Disk accretion ceases after $\sim 10^6$ yr, and the pre–main-sequence star or class III object continues to contract toward the main sequence for the next 10^7 yr. During this time, material in the disk may coagulate into a planetary system. The search for disks and their evolution from the embedded phases to the main-sequence is reviewed by Beckwith & Sargent (1996).

This schematic picture of the formation of a low-mass star is based on a wealth of, primarily, continuum observations from millimeter to near-infrared wavelengths. It offers a valuable framework for further theoretical and observational work, in particular to constrain the detailed physics which determine the structure and evolution of the envelopes and disks. Of special interest is the interdependency of the outflow and the envelopes, since accretion is the driving mechanism behind the outflow, while entrainment of material in the outflow is an important factor in the dispersal of the envelope. This thesis will focus on a number of important questions about the evolution during the embedded phase, which can only now be addressed for a sizable group of YSOs with new and improved observational facilities at (sub)millimeter wavelengths.

- What is the density and temperature distribution in the envelopes around class 0 and class I YSOs? Can we test the various theoretical models, and determine the relative importance of rotation and magnetic field on the envelope structure?
- What is the velocity field in the envelopes? Is material still falling in during the embedded stages, or has the outflow effectively halted collapse?
- How do the density, temperature, and velocity structure of the envelopes depend on the age of the source, its mass, or the star-forming environment?
- At what stage of the embedded evolution are circumstellar disks formed, and with what frequency? Do they grow in mass as increasing amounts of envelope material are accreted? How does multiplicity influence their formation and evolution?
- What is the relation between the strength of the outflow and the mass of the envelope and the circumstellar disk? How does the outflow influence the structure of the envelope?

1.2 Radiation from molecules and dust

1.2.1 Molecules...

Transitions between the rotational energy levels of molecules, identified by the quantum number J, are ideally suited to probe the physical structure and velocity fields of dense material such as the envelopes surrounding newly formed stars (cf. Jansen 1995). The lower-J transitions of most molecules lie at millimeter and submillimeter wavelengths, which are long enough to penetrate the large columns of dust which obscure the YSO at shorter wavelengths. Although the envelopes are optically thick in lines of abundant molecules such as ^{12}CO, the lines of isotopomers like ^{13}CO, $C^{18}O$ or $C^{17}O$, which have lower abundances by factors of 50–2500, provide optically thin probes. The conditions required to excite the lower rotational levels of various molecules correspond closely to the typical densities and kinetic temperatures expected in YSO envelopes, making them excellent diagnostic tools. In addition, they provide the only means to investigate the velocities of the material. Variations in the abundance of particular species, e.g., SiO and CH_3OH, may hint at processes like dust grain destruction and grain mantle evaporation. Thus, a variety of molecules may be used to probe the different physical regimes and disentangle their contributions to the emission within the telescope beam.

The excitation of the rotational energy levels of a molecule is governed by collisions, mostly with H_2 and, in some cases, electrons, and by radiation in the form of continuum or line photons. Whether a level is significantly populated depends on the energy of the level and the critical density of the transition. The former sets the typical kinetic temperature required for collisions to excite the level. The latter indicates when collisional (de-)excitation starts to dominate over de-excitation through spontaneous emission of a photon. This means that for densities above the critical density, the excitation is essentially determined by collisions and follows a Boltzmann distribution (local thermodynamic equilibrium, LTE), while for lower densities the radiation field also contributes significantly. In general, the excitation will be lower in the latter case (sub-thermal), although strong radiation fields (optically thick conditions) will drive the populations toward LTE.

Because of the dependence of the excitation on density and temperature, the intensities of different transitions are a powerful diagnostic of the physical conditions in the molecular gas, as well as the amount of material traced in the particular molecule. However, extracting this information from the observations is not simple. Various methods exist, which treat the molecular excitation, and particularly the role of radiation, with increasing levels of complexity. By far the simplest method is to assume LTE excitation. If a sufficient number of transitions of a certain molecule are observed, the intensities can be converted to column densities in each level and plotted in a Boltzmann diagram (also called a rotation diagram) (e.g., Blake et al. 1987). The slope of such a diagram is inversely proportional to the temperature. Alternatively, an estimate of the temperature can be obtained from the observed brightness temperatures of optically thick lines, which should approach the kinetic temperature. Once the temperature is constrained, molecular masses and abundances may be derived. As long as the typical densities exceed the critical densities of the observed transitions, the assumption of LTE can be safely made. For the molecules studied in this thesis, LTE excitation is valid, or at least a viable approximation, for all of the observed transitions of CO and its isotopomers. For HCO^+ and HCN, which typically have much higher critical densities, LTE is a useful approximation only for the J=1–0 transition.

The next level of sophistication is to assume that the contribution of the radiation field of the molecules is only important to the excitation locally. In that case a solution can be found iteratively, as is done, e.g., in the escape probability, the large velocity gradient, or the microturbulent methods (Sobolev 1960; de Jong et al. 1980; Goldreich &

Kwan 1974; Leung & Liszt 1976). In some chapters of this thesis, the escape probability method is used to get first-order estimates of the excitation.

The assumption that the radiation field only contributes locally is not valid, however, in YSO envelopes: the column density of material is large, while the velocity gradient is small throughout much of the envelope, so that radiative coupling occurs over large regions. In this case the molecular excitation has to be solved together with the radiation field throughout the envelope simultaneously. A very efficient method for this purpose is offered by the Monte Carlo method (cf. Bernes 1979; Choi et al. 1995). To date, applications have been limited to spherical systems. For this thesis, a Monte Carlo method has been developed which solves the radiative transfer in source geometries which may be axisymmetric. The latter is required to describe aspects like flattening, rotation, and the presence of outflows, all of which are sampled by our observations. The Monte Carlo method is described in detail in Chapter 7.

1.2.2 ...and dust

Dust makes up $\sim 1\%$ by mass of the interstellar medium, and emits at millimeter and infrared wavelengths in thermal continuum radiation. For the low-mass YSOs studied in this thesis, it is found that almost all of the continuum emission at millimeter wavelengths is due to thermal emission from dust, with only a negligible amount attributable to non-thermal processes such as free–free emission. If the temperature distribution of the dust and the emissivity of the material are known, the dust mass, and by inference the total mass, can be obtained. The value of the dust emissivity at infrared and millimeter wavelengths is a strong function of the composition and shape of the dust particles, and has been uncertain by an order of magnitude for a long time. In recent years, the uncertainty appears to have decreased to a factor of 2–3 due to the work of Ossenkopf & Henning (1994), Agladze et al. (1994), and Pollack et al. (1994). However, the possibility of coagulation in the dense environment of protostellar envelopes and disks still introduces some uncertainty. In observations which resolve the dust emission at wavelength regions longward of the mid- to far-infrared, where the emission is optically thin, the density distribution can be derived from the projected emission. Because broad-band observations of dust continuum are much more sensitive than narrow-band spectral line data, weak emission features like, e.g., circumstellar disks, are much more readily detected through their continuum emission. As such, continuum observations provide valuable, complementary information to spectral line data.

1.2.3 Chemistry in star-forming regions

Apart from the diagnostic capability of molecular emission lines, molecular abundances themselves provide valuable information about the physical conditions and processes in the YSO environment. An exhaustive review of chemistry in star-forming regions can be found in van Dishoeck & Blake (1998). Of particular interest for the observations presented in this thesis are the abundance of HCO^+, the freezing-out of molecules onto dust grains, and the destruction of dust grains in shocks generated by the outflow.

Most of our observations focus on HCO^+ as a reliable tracer of the envelopes around YSOs. This particular molecule was selected for a number of reasons. The first motivation is the temperature and density regime sampled by its low-lying rotational transitions of 10–40 K and 10^5–10^7 cm^{-3}, which, unlike the case of CO, is well-matched to the expected conditions in the envelopes. Another reason is the fact that HCO^+ is the on of the most abundant molecular ion, providing constraints on the ionization fraction of the material. This is relevant for collapse models involving magnetic fields. A third reason is that chemical models predict that the abundance of HCO^+ remains nearly constant throughout the envelope (Rawlings et al. 1992; Willacy, Rawlings, & Williams 1994). Many molecules freeze-out onto dust grains in the dense and cold environment of cloud cores (see Mundy & McMullin 1997 for a review of the observational constraints on molecular depletion in star-forming regions). CS, for example, traces the same density and temperature regime as HCO^+, but it has been found to be severely depleted in YSO envelopes (McMullin et al. 1994; Ohashi et al. 1996b), limiting the sensitivity of a survey in transitions of this species. An important formation route of HCO^+ is $CO + H_3^+ \rightarrow HCO^+$. The constant abundance of HCO^+ is explained by the increase in the abundance of H_3^+, when the main removal partners of the latter (CO, O, H_2O, ...) freeze-out onto grains. Our observations confirm the expected sensitivity of HCO^+ as a probe of the envelopes around YSOs.

Another aspect of the chemistry in star-forming regions illustrated by our observations is the sputtering or destruction of grain particles in shocks generated by the bipolar outflow. The association of SiO with shocked material is witnessed by its broad line profiles (e.g., Bachiller 1996). Schilke et al. (1997) show that shocks of the order of 25 km s^{-1} are capable of generating the observed columns of SiO. The silicate released by the break-up of dust particles rapidly reacts with O_2 or OH to form SiO. Other molecules are also found to trace the interaction of the outflow with ambient material, and probably originate from the evaporation of the ice mantles as the gas is heated (e.g., van Dishoeck et al. 1995).

1.3 Aim and outline of this thesis

1.3.1 Aim of this thesis

The picture of the formation of a low-mass star sketched in §1.1.2 leaves a number of important questions unanswered, in particular those concerning the structure of the envelopes surrounding embedded YSOs, their comparison to theoretical models, the presence of circumstellar disks during this phase, and the connection between the outflow and the envelope. In this thesis, the physical structure of a limited but well-defined sample of low-mass YSOs is constrained by a variety of techniques. An important by-product of this study is an investigation of which type of observations provide the most powerful probes for such studies. The ultimate aim is to identify important physical processes and diagnostic observations which can be applied to a much wider sample of YSOs in future studies, in order to statistically investigate their evolution and the dependence on star-forming environment.

Studies of the physical structure of YSOs have become possible owing to the observational developments at (sub)millimeter wavelengths in the last five years. The sensitivity of high-frequency detectors has increased by an order of magnitude. This allows observations of the line profiles of weak molecular transitions which uniquely trace the density, temperature, and velocity structure on scales of a few thousand AU, providing sensitive tests of various collapse models. The extension of millimeter interferometers from three to 6–9 telescopes has resulted in much faster imaging capabilities, so that a whole sample of objects can now be studied on scales of a few hundred AU in the lower rotational lines of a suite of molecules.

Our source sample consists of thirteen embedded YSOs, nine located in the Taurus-Auriga complex ($d \approx 140$ pc) and four in the Serpens molecular cloud (400 pc). The Taurus sources were chosen from the flux- and color-limited sample of 24 embedded YSOs selected from the IRAS point source catalog (Tamura et al. 1991). Of these 24, 15 are class I sources, while 9 are optically visible T Tauri stars. On the basis of the strength of their HCO^+ 3–2 emission as observed by us in a 19$''$ beam, nine of these YSOs were selected for further investigation. Only two of these are optically visible T Tauri stars (including T Tau itself), and both have more embedded companions. One source is invisible even at 4 μm and is sometimes referred to as a class 0 object. However, its almost edge-on inclination suggests that geometry may play an important part in its "young" appearance.

The four YSOs in Serpens, all class 0 objects visible only at far-infrared and longer wavelengths, extend our study to an earlier evolutionary phase. These sources are also somewhat more massive, possibly intermediate-mass, stars. In addition, Serpens is forming stars at a much higher spatial density than Taurus. Taken together, both samples provide a detailed view of the embedded phase of star formation in sparse and dense environments. With thirteen sources, the sample is small enough to study in great detail, but still large enough to separate individual characteristics from general trends, and to set a baseline for future studies involving statistically robust samples.

The data set obtained consists of single-dish observations of lines of various molecules including CO, HCO^+ and HCN and their isotopomers, which trace the densities (10^4–10^7 cm^{-3}) and temperatures (10–100 K) expected in YSO envelopes on scales of 10$''$–30$''$ (1400–4200 AU at the distance of Taurus, 4000–12000 AU in Serpens). These observations are complemented by interferometric data on 3$''$–5$''$ scales of the 1–0 transition of these same species, which sample the envelope structure and the interaction of the outflow with the envelope material on scales of several hundred AU. Continuum measurements in the interferometer beam, combined with single-dish data from the literature, sample the dust content of the envelopes and circumstellar disks of the sources.

Our data set samples a large range in physical conditions and spatial scales, which distinguishes this work from previous studies which were often based on a single line in a single object. The great wealth of, often complementary, information gathered on the source sample allows a detailed analysis of the YSO environment. Since the sources are embedded in extended envelopes, much of the flux is resolved out by the interferometer observations. Reliable conclusions can only be derived through careful analysis and comparison to single-dish observations which contain all flux. The Monte Carlo codes, which were developed specifically for this work, forms an essential element in the interpretation of the data.

1.3.2 Outline

Chapters 2 to 5 present the observations of the Taurus source sample and their analysis. The aperture-synthesis continuum data and the HCO^+ single-dish emission are discussed in Chapter 2. These data reveal the presence of circumstellar disks and provide estimates of the mass of the circumstellar envelopes. The HCO^+ single-dish lines are found to be excellent tracers of these envelopes, which can be described by the simple inside-out collapse model or related density power laws. Chapter 3 analyses the single-dish CO data to obtain constraints on the excitation conditions in the envelopes and outflows. ^{12}CO 3–2 maps of the outflows provide valuable information on the geometry of the systems, and delineate the link between outflow strength, envelope mass, and disk continuum flux. The aperture-synthesis line observations probe the envelope structure on 700 AU scales, revealing the central, flattened region of the envelope, material being influenced by the outflow, and scattered clumps throughout the envelopes.

In Chapter 4 a simple model is presented for the contribution to the envelope heating by scattered ultraviolet radiation generated as material accretes from the disk onto the star. This process can have a significant influence on the temperature structure of the envelopes, and may explain (part of) the observed ubiquitous ^{12}CO and ^{13}CO 6–5 emission. Interferometer continuum data at 1 mm with subarcsecond resolution are presented in Chapter 5 of the young binary T Tau, revealing the presence of a disk around T Tau N and offering a possible explanation of the obscured nature of T Tau S.

Chapter 6 turns the attention to the Serpens sample, presenting single-dish and aperture-synthesis observations. From their continuum emission, a density distribution is fit to the envelopes, which also reproduces the essentials of the molecular line emission. It is found that the observations of these more embedded and somewhat more massive YSOs can be interpreted within the same, simple, framework as the class I Taurus sources.

In Chapter 7 the simple analyses of the previous chapters are refined by detailed model calculations of four typical sources adopted as templates. The spherically symmetric inside-out collapse model serves as a reference for calculations involving rotation and the presence of a weak magnetic field, to study the effects of an axisymmetric, flattened geometry. To describe the interaction of the outflow with the surrounding envelope a simple mixing layer model is constructed, which reproduces a number of interesting features present in the interferometer observations.

The thesis concludes with a bibliography and a summary in Dutch.

1.4 Conclusions and future work

The data and model calculations presented in this thesis offer a detailed and complete picture of the molecular environment around low-mass YSOs on scales between a few hundred and several thousands of AU. Important physical processes determining the appearance of the emission are identified, and a combination of observations and model calculations is defined which can help to efficiently constrain the conditions in the envelopes of a large sample of YSOs. For detailed results of the individual chapters the reader is referred to the abstracts preceding each of them. Here, the most important, overall conclusions of this thesis are summarized.

1. Throughout the entire embedded phase, the density in the envelope can be described by a radial power law with slope between -1 and -2, as expected from theoretical models. The molecular line profiles observed in single-dish beams are reproduced by the spherically symmetric inside-out collapse model of Shu (1997). This indicates that this formulation captures well the essentials of the envelope structure on scales of a few thousand AU and more. Single-dish molecular line observations coupled with detailed modeling provide a sensitive tool to study the envelope structure throughout the embedded phase, while continuum observations alone are largely limited to the early, class 0 phase.

2. Both the envelopes of the Serpens sources and those of the Taurus sources can be described by the same model, although model parameters like age and sound speed are different. This suggests that the essential physics of the collapse process is the same in the low-density Taurus region and the densely star-forming Serpens cloud.

3. A good correspondence between calculated and observed line and continuum intensity is found for an adopted temperature structure characterized by a power law with a slope of -0.4, as would be expected when the heating is dominated by infrared radiation from the central object and optically thin conditions in the envelope. Only in the inner few hundred AU of the dense Serpens envelopes is the temperature likely to exceed this behaviour because of opacity effects. This confuses the detection of possible circumstellar disks around the Serpens sources (see below). Scattered ultraviolet emission originating at the boundary layer between the star and its disk may contribute significantly to the heating of the envelopes if typical densities are below $\sim 10^5$ cm^{-3}. This has been proposed as an explanation of the observed narrow ^{13}CO 6–5 emission, but the extent to which it competes with the heating by infrared radiation from the central object remains to be investigated.

4. On the smaller scales of 700–1500 AU sampled by the interferometer the envelopes show deviations from the spherical symmetry which suggest flattening and rotation. These characteristics can be reproduced by the inclusion of rotation and a magnetic field in the collapse model. A uncomfortably large rotation rate is inferred, however, and a model description which combines rotation and magnetic fields, and which smoothly joins the infalling envelope with a circumstellar disk is warranted.

5. Embedded YSOs are characterized by a large amount of emission on extended scales, which is resolved out by the interferometer. To derive molecular abundances on these small scales it is of vital importance to incorporate a measure of the total flux either by directly adding the missing zero-spacings, or by including single-dish observations of other transitions of the same molecule in the model calculations.

6. While the single-dish line profiles predicted by the model calculations invariably show the blue infall asymmetry when self-absorption is present, the observed spectra reveal a much larger variety in profile shape. This can be understood in terms of the different sensitivity of various lines to the presence of optically thick surrounding

cloud material. The HCO^+ 3–2 and 4–3 lines are found to almost exclusively trace the envelopes, and it is their line profiles which offer the best diagnostic of the infall velocity field. Their observed line profiles show that, as long as the envelopes are massive enough to create self absorption, the infall asymmetry is present throughout the full extent of the embedded phase.

7. Unresolved circumstellar disks are readily identified in interferometer continuum observations of many class I sources at the obtained sensitivity. Their identification is essential for the interpretation of the continuum fluxes in single-dish beams, which often contain significant contributions from these disks. Based on their fluxes, there is no apparent trend in disk growth from the class I to the class II phase. However, direct comparison is difficult, because of the ten times longer duration of the class II phase. The identification of disks in the deeply embedded class 0 phase is prevented by the dense and highly concentrated envelope emission, which generates a strong unresolved component that swamps any disk emission. Observations at much higher angular resolution of $0''.3$ or better, e.g., through JCMT–CSO single-baseline interferometry at high frequencies, are required to study the actual formation period of disks.

8. The detection of an unresolved circumstellar disk around only one member, T Tau N, of the young binary system T Tau illustrates the different formation histories of such disks in the presence of a companion star. The observations also suggest a possible explanation for the infrared nature of T Tau S, if this star is located in projection behind the obscuring, outer edge of the disk surrounding T Tau N. This may resolve the question of why two members of a close binary pair are in apparently different evolutionary stages, and may apply to other such known systems.

9. The outflow strength of class I sources is correlated with the bolometric luminosity, the envelope mass, and the millimeter flux of the disk. This may indicate that denser and more massive envelopes sustain larger infall rates, resulting in higher accretion rates in the disk, generating more disk flux and a stronger outflow. If supported by further observations, this suggests an interesting feedback mechanism, whereby the envelope regulates the strength of the very outflow which is responsible for its dispersal.

10. The direct impact of the outflow on the surrounding molecular envelope is traced by bright HCO^+ and HCN emission on interferometric scales. A simple model describing this interface as a mixing layer explains the essentials of the small scale HCO^+ and HCN emission together with the ^{12}CO line wings. Only a small fraction of $< 1\%$ of the total envelope mass is incorporated in the mixing layer, which puts a limit on the amount of material directly influenced by the outflow at any moment. However, if this mixing layer proceeds into the surrounding cloud by only a few tenths of a km s^{-1}, it may disperse the complete envelope in the typical duration of the embedded phase of a few times 10^5 yr.

The work presented in this thesis suggests a number of avenues for future research into the evolution of the envelopes and disks around low-mass YSOs. The envelope structure on scales of a few thousand AU of a large, statistically valid sample can be constrained from a limited but well-chosen single-dish data set, containing lines of various optical depth of CO, HCO^+, and their isotopomers. Using spherically symmetric

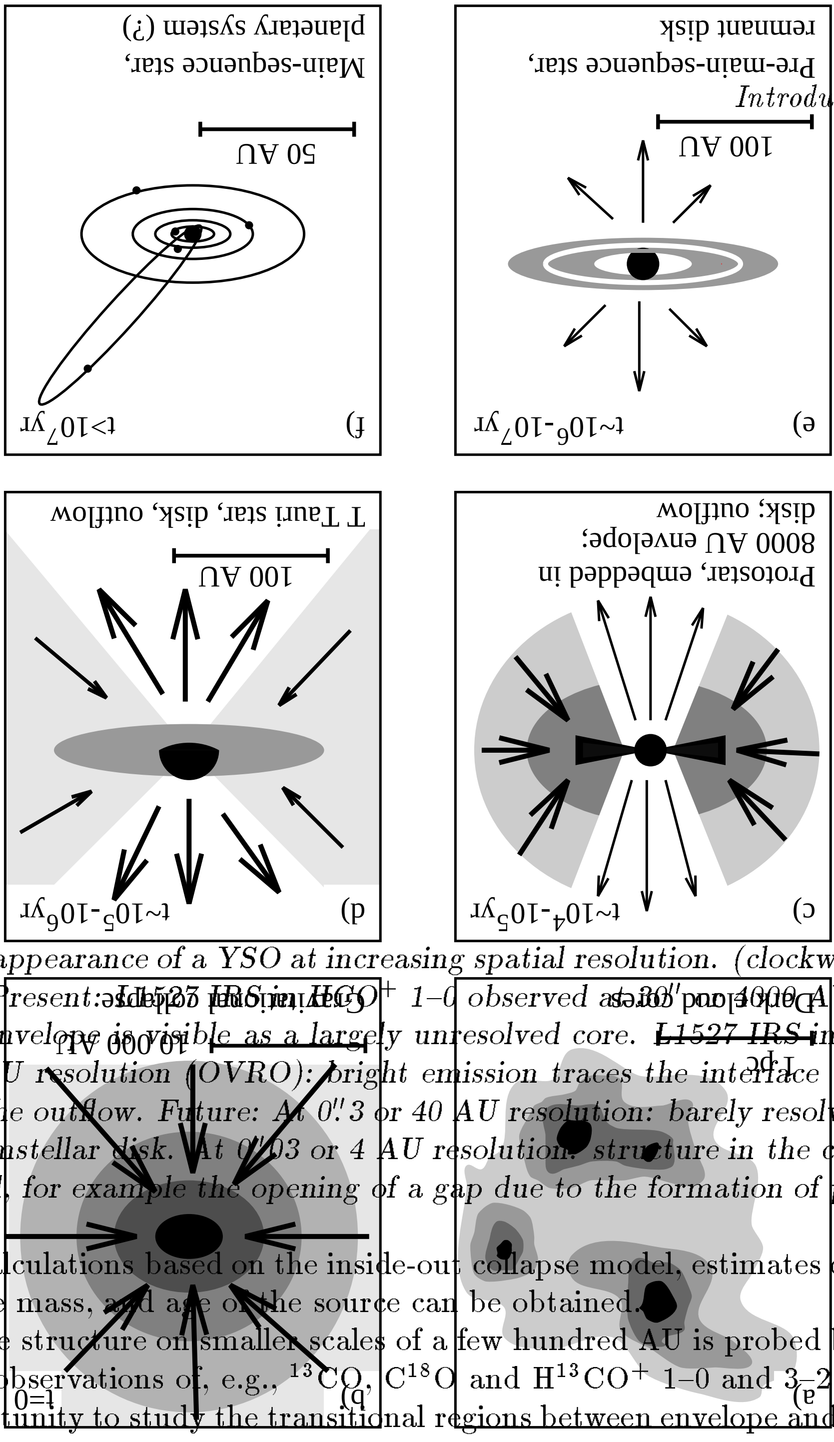

Fig. 1.2. *The appearance of a YSO at increasing spatial resolution. (clockwise, starting at upper left) Present: L1527 IRS in HCO$^+$ 1–0 observed at 30″ or 4000 AU resolution (JCMT): the envelope is visible as a largely unresolved core. L1527 IRS in HCO$^+$ 1–0 at 3″ or 400 AU resolution (OVRO): bright emission traces the interface between the envelope and the outflow. Future: At 0.″3 or 40 AU resolution: barely resolved emission from the circumstellar disk. At 0.″03 or 4 AU resolution: structure in the circumstellar disk is revealed, for example the opening of a gap due to the formation of planets.*

Monte Carlo calculations based on the inside-out collapse model, estimates of the sound speed, envelope mass, and age of the source can be obtained.

The envelope structure on smaller scales of a few hundred AU is probed by the aperture synthesis observations of, e.g., ^{13}CO, C^{18}O and H^{13}CO$^+$ 1–0 and 3–2, offering an excellent opportunity to study the transitional regions between envelope and circumstellar disk. Comparison with similar work on the gas disks during the later T Tauri stage is especially interesting. With the increased resolving power of future (sub)millimeter interferometers, these disks can be studied in detail, as is illustrated in Fig. 1.2.

The mixing layer model for the interferometric HCO$^+$ and HCN observations proposed by us offers a promising tool to investigate the dynamics and chemistry of the interaction between two moving fluids. In particular, it allows a direct investigation into the way the outflow disperses the molecular envelope and halts collapse. This is one of the least understood processes operating during the formation of a star, but may have important implications for the distribution of formed stellar masses and the efficiency of star formation on galactic scales.