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High angular resolution studies of protoplanetary discs

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CHAPTER 1

Introduction

THROUGHOUT our lives, we unknowingly observe the final stage of circumstellar disc evolution: our planet orbiting the Sun. The origin of planets and the uniqueness of Earth have been the motivation to explore beyond the Solar system and into our Milky Way Galaxy, which we can see stretched across a cloudless night sky. In the youngest regions of the Galaxy, where stars like our Sun are being born, we look for answers to how the planets, gaseous giants like Jupiter or small rocky planets like Earth, form. It is in these star-forming regions that we find evidence that the planets of the Solar system all formed in a single disc of gas and dust, extending from near the central star to hundreds of times the Earth orbit. This thesis relies on data from instruments often used in the media as examples of human technological achievement: interferometric arrays of antennas operating in the submillimetre wavelength regime (see image on page 149), that are able to observe the structure of young protoplanetary discs hundreds of light years away. It focuses on constraining the mass of dust and gas that discs are made of, and how this material is distributed from the star outwards. The underlying physics that is studied in this thesis touches on processes of direct interest to planet formation: dust grain growth and migration, gas dispersal, as well as on the presence of planets or other bodies within these discs suggested by disc asymmetry. Future instruments, in particular the Atacama Large Millimeter Array, consisting of 66 antennas at 5000 m elevation in the Chilean Andes and being built through a joint worldwide effort including Europe, will allow a major leap forward in our understanding of discs and how planets are formed within them.

1.1 HOW IT ALL BEGINS

Low-mass star formation begins in *molecular clouds* made of molecular gas and dust, regions of low density ($\approx 10^3$ particles per cm^{-3}), that can be more than 100 pc in size (e.g. Ungerechts & Thaddeus 1987; Alves 2004). Some of the nearest and most studied star-forming regions are Taurus-Auriga, Orion and Ophiuchus. The temperature in these regions is dominated by the interstellar radiation field and cosmic ray ionisation and can be as low as 10 K. Molecular clouds are readily observed in the submillimetre, via rotational transitions of CO (e.g. Ungerechts & Thaddeus 1987) or dust extinction (e.g. Lada et al. 2007). Parts of clouds undergo a collapse to form denser regions, the process led by gravity and regulated by the cloud turbulence and other factors. In about 10^5 yr, ten to hundred times denser and much smaller regions ($\approx 10^4$ AU), called *dense clouds*, are formed (See the recent review by Bergin & Tafalla 2007, and references therein). First discovered by W. Herschel in 1784 as regions where stellar light was lacking, or as ‘holes in heavens’ as he exclaimed, these clouds were later identified in interstellar extinction maps as regions of high-extinction and reddening, seen in silhouette against the background light (e.g., Barnard 68, Alves et al. 2001). The dense clouds with no central object, which often exhibit evidence of an ongoing contraction seen in the submillimetre mapping of the lines of CO and other molecular species (e.g. Tafalla et al. 1998; Caselli et al. 2002), are believed to be on the way to form proto-stars and are called *pre-stellar cores*. Their temperature is ≈ 10 K, due to their higher density with respect to the molecular clouds. The process of contraction is led by gravity and regulated by the ‘magnetic braking’ through ambipolar diffusion (Shu 1977; Mouschovias & Ciolek 1999) and/or the dissipation of turbulence via shocks (e.g. Mac Low & Klessen 2004). The central object is formed, and it begins to heat the surrounding core by radiating away the excess gravitational energy released during contraction. At this stage the density and temperature conditions in the core make it rich in chemistry, with an increase in abundance of complex molecules (e.g. van Dishoeck 2006). Eventually, a *young stellar object* (YSO) is formed, embedded in the envelope material (Lada & Kylafis 1998; Evans 1999; Mannings et al. 2000; Reipurth et al. 2007). This is commonly called the ‘Class 0’ stage. The material close to the star is accreted through a dense and hot disc, and funneled onto the star along the magnetic field lines. The envelope material is being accreted onto the disc as the disc viscously spreads outwards, processes dominated by the angular momentum, gravity and the magnetic field. YSOs are identified by a notable infrared emission, while the stellar photospheric emission is heavily obscured by the surrounding envelope. The embedded stage in which the envelope dominates the spectral energy distribution (SED) of the object (‘Class 0’ and ‘Class I’) lasts about 0.5 Myr (Evans et al. 2009) and often exhibits outflows that partially clear away the envelope. In the following, ‘Class II’ stage, the viscous accretion disc (Adams et al. 1987, 1988) extends several hundreds of AU from the star, with the outer edge determined by photoevaporation due to the interstellar radiation field or truncation by a companion. The envelope mass is small with respect to the disc mass, and no longer obscures the young star. The stellar photospheric emission is observed, as well as the excess emission in the infrared and submillimetre, arising from the disc. The work presented here concerns this last stage.

1.2 DISC PHYSICAL PROPERTIES

The discs around young stars extend up to 1000 AU in radius (Piétu et al. 2005; Isella et al. 2007). About 99% of the disc mass is contained in the gas. This is primarily molecular gas, with H_2 being the most abundant molecule followed by CO, with some atomic gas, mainly He. The gas rotates around the star in slightly sub-Keplerian motion due to gas pressure and viscosity¹. The remaining 1% of the mass is contained in dust. Dust is generally well coupled to the gas and thus in sub-Keplerian rotation, with the exception of particles large enough to decouple from the gas and which may consequently drift inward. The disc is heated primarily by the radiation field of the central star (see, e.g. Dullemond et al. 2007), which is absorbed in the inner rim and surface disc layers where the optical extinction $A_V \leq 1$ mag. Almost all of the energy is absorbed and reprocessed by the dust, and these processes determine the disc gas temperature throughout the disc, except in the uppermost disc surface layers where gas and dust are decoupled, and the densest midplane layers in the inner few AU where viscous heating may be a dominant process. In turn, the gas provides pressure that maintains the disc vertical structure enabling the dust to be exposed to the stellar light (Jonkheid et al. 2004, 2007). Almost every major process involving one of the two components, dust or gas, affects the other significantly. Dust coagulation and settling toward the disc midplane disables the photoelectric heating process and may lead to a decrease of the gas temperature in the surface layers. Vertical mixing within the disc stirs the dust up along with the gas and opposes the dust settling. When dust drifts inward due to the loss of angular momentum to the sub-Keplerian gas, the outermost disc regions remain exposed to the interstellar radiation field and the gas may be photodissociated more efficiently there. Gas ionisation enhances the influence of the magnetic field on the disc, which, through the so-called ‘magneto-rotational instability’ (MRI; Balbus & Hawley 1997) leads to turbulence and an effective angular momentum transport.

It is because of the mutual dependence of gas and dust in shaping the disc that both these components need to be observed, modelled and analysed simultaneously when studying disc structure (Qi et al. 2004; Raman et al. 2006). This thesis shows how this approach yields results that could not be obtained by investigating the two components independently.

During the evolution of the disc, the gas is largely accreted onto the star, but also thought to be dispersed and photoevaporated (Shu et al. 1993; Matsuyama et al. 2003), while the dust in the inner disc dissipates typically within 10 Myr (Hillenbrand 2008). The dust settles to the disc midplane and coagulates, and the dust growth process is most efficient in the dense midplane where large particles may drift radially, against the gas pressure (Whipple 1972; Weidenschilling 1977; Brauer et al. 2008). All these processes change the appearance of the discs: young discs are gas-rich and their dust is well mixed with the gas, while old discs have very little gas, with dust that has already grown to significant sizes and is no longer dominated by gas pressure. However, the age of the star does not seem to be a good indicator of the evolutionary stage of the

¹This is not the viscosity in its conventional definition, but a parametrisation of the energy dissipation mechanism, necessary for the accretion of matter through the disc.

disc (Cieza et al. 2007; Evans et al. 2009). This implies that the disc evolution is a more intricate matter, and depends on the environment in which the star and disc are born: their initial masses, angular momentum, and magnetic field for example. In this sense it is interesting to study discs of all types, gas rich or not, to try to disentangle the possible evolutionary trends.

Based on the mass of the central star, the discs around young pre-main sequence stars have different nomenclatures. The low-mass young stars, with $M \leq 1 M_{\odot}$ and spectral types from late F to early M, are called T Tauri stars, their prototype being the famous young variable star T Tau (Joy 1945; Ambartsumian 1957; Herbig 1962). The discs attributed to T Tauri stars are observed to be typically a few hundred AU in size, have the gas + dust mass 10^{-3} - $10^{-1} M_{\odot}$ (Beckwith et al. 1990; Andrews & Williams 2007), and are relatively cold due to the low stellar luminosity. The intermediate mass stars, with mass 1.5 - $8 M_{\odot}$, are called Herbig AeBe stars after their definition given in Herbig (1960). As the name suggests, they have A and B spectral types. Their discs are observationally similar to those around T Tauri stars (Mannings & Sargent 1997; Beckwith et al. 1990) but warmer. Stars of higher masses with discs are not frequent but a few examples are found in the literature (Patel et al. 2005; Sandell et al. 2003; Alonso-Albi et al. 2009). These discs are believed to evolve rapidly due to the strong stellar radiation field. This thesis focuses on the discs around T Tauri and Herbig Ae stars, both formed by the same low-mass star formation mechanism as outlined in Section 1.1.

1.3 FEEDBACK FOR PLANET FORMATION

An ever growing number of the newly discovered extra-solar planets and planetary systems provide evidence that a possible outcome of disc evolution is a planetary system (e.g. Udry & Santos 2007), and there is an ongoing effort to understand which conditions in discs are necessary to form a habitable planet like Earth. The distribution of mass with distance from the star in the extra-solar planetary systems and in our own Solar system may carry some imprint of how the mass in the planet-forming regions of their predecessor discs was distributed. Some information about the chemical composition of gas and dust in the pre-solar nebula is encrypted into the cometary material which we can observe and study (Ehrenfreund et al. 2004). However, an important part in understanding planet formation is looking back in time, to the earliest phases of planet formation, and this is done through the observations of discs around young stars.

It is observationally challenging to probe the physical conditions in the planet-forming regions of discs directly (a few tens of AU from the star), as these observations require subarcsecond spatial resolution. Furthermore, the emission of gas and dust arising from these regions (in the near- and mid-infrared wavelength regime) is optically thick and does not probe beyond the surface of the disc. However, a number of physical processes that influence the planet formation leave their signatures in the disc structure at larger scales that can be probed via optically thin dust and molecular gas tracers. Also, planets themselves can leave a signature on the larger scale disc structure

in the form of gaps, inner cavities, and clumps (Lin & Papaloizou 1993).

The disc is formed through the accretion process of circumstellar material from the proto-stellar envelope. This material is distributed spherically at scales of several thousands of AU, and accretes on to the plane of rotation at relatively small distances from the star (a few to a hundred AU). The subsequent viscous spreading of the accretion disc until its final size of typically 200 AU or more (Hartmann et al. 1998) determines the overall disc structure. The amount of mass in the envelope and the initial angular momentum play a major role in how the mass is accreted on to the disc, while the disc's viscous properties, linked to the effect of magnetic field on the turbulence within the disc along with the disc density, shape the disc as it spreads (Hartmann et al. 2006; Matsuyama et al. 2003). Irradiated accretion disc models and passive irradiated disc models provide disc structures consistent with the broad-band SEDs of discs (Dullemond et al. 2001; Calvet et al. 2004; D'Alessio et al. 2005; Dent et al. 2006, Chapter 2 of this thesis) and spatially resolved dust millimetre interferometer observations (Isella et al. 2009, Chapter 6 of this thesis), and are widely used. The densest, planet-forming regions (disc midplane up to few tens of AU from the star), are not directly probed, because emission arising from these regions is optically thick, and their properties are extrapolated from the model fits to the outer disc or other indirect methods.

Physical parameters like the radial distribution of material, gas-to-dust mass ratio and the reservoir of gas available for the formation of gas giants, are essential for the understanding of these disc regions. They need to be extrapolated from the studies of larger-scale disc structure. Abovementioned viscous accretion disc models have surface density distributions (the vertical column density) $\Sigma \propto R^{-p}$, with $p \approx 1$ throughout the disc. This value is consistent with the measurements of p in the outer disc of some sources (Pinte et al. 2008; Wilner et al. 2000; Andrews & Williams 2007; Isella et al. 2009).

1.4 OBSERVATIONS OF PROTOPLANETARY DISCS

The observational properties of young low-mass stars, like ultraviolet and infrared excess or flaring activity, encouraged the idea that young stars may be surrounded by circumstellar discs (Herbig 1962; Mendoza V. 1966). In the near-infrared speckle interferometric observations of (Beckwith et al. 1984), compact elongated infrared emission was detected towards two young stars, and associated with circumstellar discs. Sub-millimetre interferometry followed shortly with more evidence for circumstellar discs (Beckwith et al. 1986; Sargent & Beckwith 1987), until developing its full potential in the last ten years and resolving disc structure with instruments mentioned in Sect. 1.5. The first images of discs taken with the Hubble Space Telescope (HST) (Burrows et al. 1996), marked the beginning of intensive and ever growing research over the past decade focusing on discs around young stars, their structure and implications this may have for planet formation. Other observational methods like scattered light imaging with HST (see Padgett et al. 1999; Grady et al. 1999, and later work by these authors) have improved our understanding of disc structure. Grain properties are studied via the mid-infrared spectral features of dust (Bouwman et al. 2001; van Boekel et al. 2003;

Forrest et al. 2004), while interferometry in the mid-infrared has allowed to spatially resolve inner disc regions (van Boekel et al. 2004; Leinert et al. 2004). This thesis uses a range of observational methods, with an emphasis on the submillimetre interferometry at high angular resolution, to study the disc structure and compare the dust and gas components in discs.

Due to the range of temperatures found in them, discs can be observed at wavelengths from the near-infrared to millimetre. This fact has enabled the disc modelling based on their SED (e.g. Dullemond et al. 2007). An example of an SED is shown in the bottom-right panel of Fig. 1.1, for the star DoAr 21 studied in Chapter 4 of this thesis. The observed fluxes (symbols) beyond $10\ \mu\text{m}$ exceed the stellar photosphere, represented by the full line, and this excess is attributed to the circumstellar material. Although the continuum fluxes are due entirely to the dust emission, which is a minor fraction of the disc mass, general characterisation of the disc is possible, distinguishing between flat and flared disc structures (Dullemond & Dominik 2004a,b), with or without an inner cavity (Forrest et al. 2004; D'Alessio et al. 2005) - all generally indicative of the evolutionary state of the disc. However, the SED is only sensitive to the inner few hundred AU which is not necessarily the entire disc. Some information about the disc size and inclination can be derived in discs based on their spatially unresolved low- J ^{12}CO line spectra (Chapters 5, 6 and 7), particularly when the line is optically thick. Yet, an image is worth a thousand words, and in case of a molecular line image - at least as many spectra as the number of the resolution units in it. An example of the spatially resolved dust emission is seen in the bottom-left panel of Fig. 1.1 where the warm dust imaging in the mid-infrared of the same source provides insights into the spatial extent of the circumstellar material. In this case, the disc is highly asymmetric, has a large inner hole and the emission extends to 200 AU or $1''.6$. To probe the radial distribution of material and disc dust mass, optically thin millimetre continuum emission is perfectly suited. Spatially resolved observations can be obtained using millimetre interferometry (see Sect. 1.5). An example of the spatially resolved millimetre continuum emission from the disc around IM Lup (Chapter 3) is given in the bottom-middle panel of Fig. 1.1. These observations are indicative of the disc radius, but in order to probe the disc extent fully, observations of cold molecular gas are necessary. The upper-middle panel of Fig. 1.1 shows observations of the low-energy rotational transition of ^{12}CO of the same disc. The comparison with the dust continuum shows how the relatively compact dust emission may be deceiving. Only with the ^{12}CO observations, we were able to probe the entire disc structure and unveil an interesting structural discontinuity in this large disc (Chapter 3). Furthermore, the molecular gas lines provide kinematical information that can be used for determination of the mass of the central star in sources at sufficiently high inclination (Chapter 3). Observations of the molecular lines of different optical depth, like ^{12}CO , ^{13}CO and C^{18}O $J=2-1$, allow us to probe the disc vertical structure and test the SED models as shown in Chapters 2 and 3. In the discs at late stages of evolution, with a low amount of material, these lines may be too weak to observe, and there the near-infrared imaging of the main gas component H_2 is an interesting prospect. This new method of tracing disc surface and geometry, discussed in Chapter 4, has allowed us to probe the surprising arc structure

around DoAr 21 as seen in the upper-left panel of Fig. 1.1.

1.5 SUBMILLIMETRE INTERFEROMETRY

With the advent of the submillimetre interferometer facilities, like the Submillimeter Array, Plateau de Bure Interferometre (PdBI), Combined Array for Millimeter Astronomy (CARMA), and others, it has become possible to investigate the outer regions and global structure of the discs around young stars through various molecular line tracers and study the dust grain growth through the thermal continuum emission of the dust (Sargent & Beckwith 1987; Kawabe et al. 1993; Guilloteau & Dutrey 1994). The advantage of these observations over spatially unresolved observations is that the disc emission is successfully separated from the more extended envelope or cloud emission and that the disc radial and vertical structure can be probed. The submillimetre emission, more than at any other wavelength, probes the full extent of the discs, from the hot inner disc regions at several tens of AU from the star to the cold outermost regions up to a 1000 AU from the star.

The principle of submillimetre interferometry is in its essence similar to the interferometry at any other wavelength. Individual telescopes are distributed over an area and linked together to overcome the technical difficulty of building a single extremely large telescope, and to obtain an equivalent spatial resolution. The signal from the source is correlated for each pair of antennas, taking into account the delay with which the wavefront meets the individual antennas. The correlation obtained (correlated flux) is associated with a (u,v) coordinate describing the distance between the two antennas and its orientation, projected onto a plane normal to the direction of the source, i.e., the plane of the wavefront. Due to the Earth rotation, a static spatial distribution of interferometre elements provides a sampling of the (u,v) plane in the course of an observing run (typically several hours). In principle, small (u,v) distances probe emission coming from a larger spatial scale while greater (u,v) distances probe emission on small scales. This is best seen when the correlated flux is plotted as a function of (u,v) distance as shown in Fig. 1.2. For the typical distance to the nearby star-forming regions (140 pc) the resolution as high as $0.3''$ (50 AU) provided by current interferometers is sufficient to resolve the structure of the discs, objects typically a few arcseconds (a few hundreds of AU) in size.

Because the sampling of the (u,v) plane is never complete, the visibility data need to be processed in order to (re)construct the image of the source starting from the Fourier transformed, *partial* source brightness distribution. The ASP publication *Synthesis imaging in radio astronomy* (1999) is a good reference for the details of the complex process of interferometer data reduction. For the scope of understanding the data presented in this Thesis, it is sufficient to note that the visibility data are true measurements of the signal from the source, probing large scales at short baselines and smaller scales at longer baselines. The spectral lines and two-dimensional images are a reconstruction (model) of the source emission based on the visibility data and these representations may differ depending on the particular schemes used in the data reduction process. For all the interferometer data presented in this Thesis, both the visi-

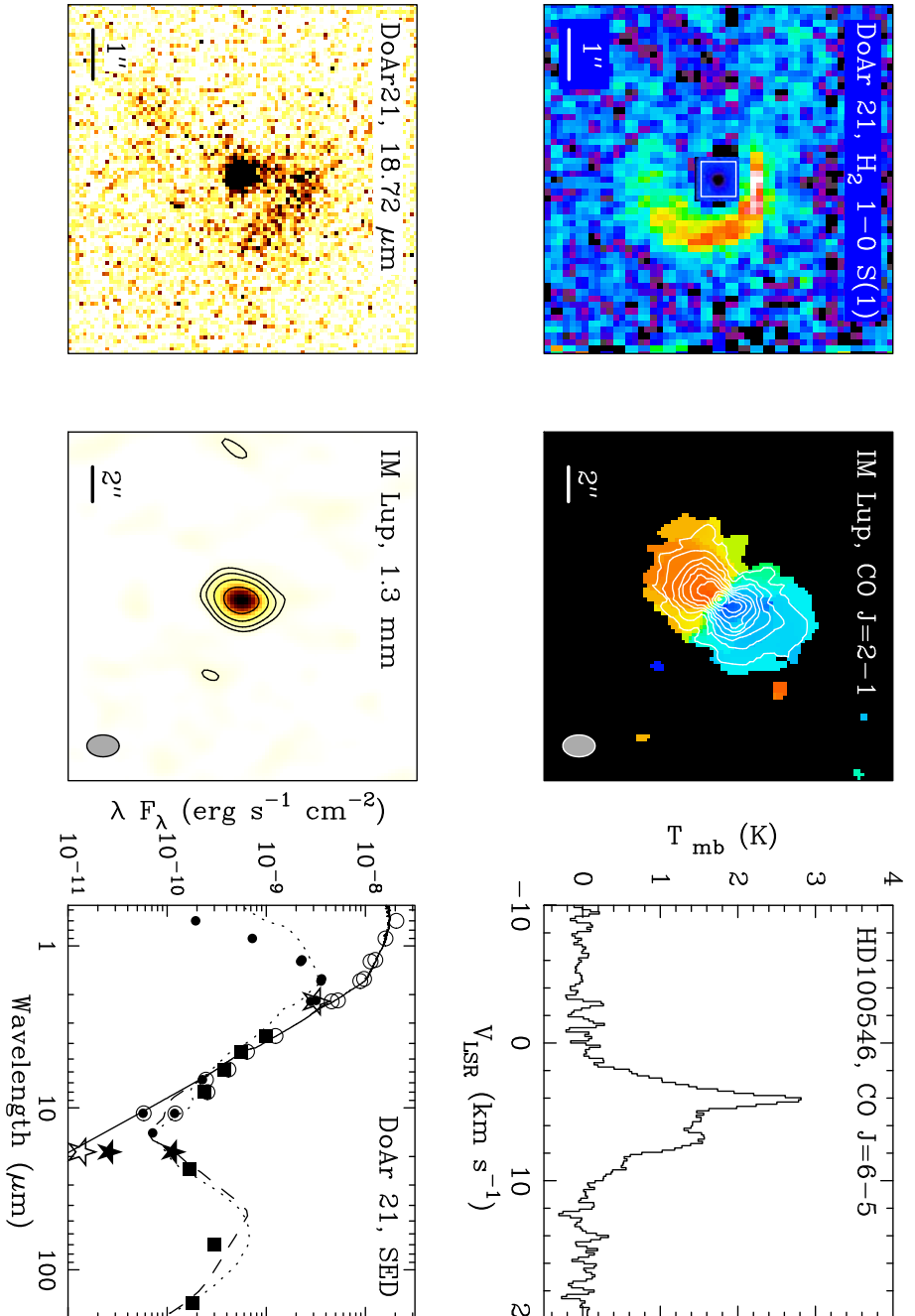


Figure 1.1: Some of the observations of circumstellar discs presented in this thesis. Upper row shows gas observations and the lower row dust observations. Clockwise: Spatially resolved imaging of the fluorescent H_2 $2.1 \mu\text{m}$ line emission towards DoAr 21 (Chapter 4); Millimetre interferometric imaging of the ^{12}CO $J=2-1$ line in the disc around IM Lup (Chapter 3); Single dish observations of the ^{12}CO $J=2-1$ line spectrum toward HD 179614 (Chapter 5); Wide-band spectral energy distribution of DoAr 21 (Chapter 4); Dust thermal continuum image of the disc around IM Lup (Chapter 3); Warm dust imaging at $18 \mu\text{m}$ towards DoAr 21 (Chapter 4). The distances to these sources are 100–200 pc. See the respective chapters for detailed description.

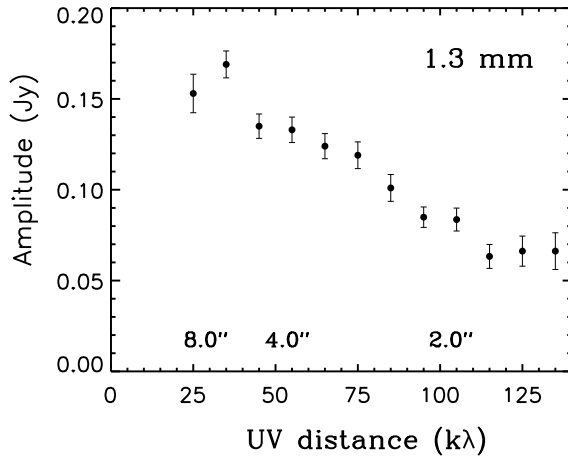


Figure 1.2: Correlated flux as function of uv-distance of the thermal continuum emission at 1.3 mm (230 GHz) towards the disc around HD 169142. The corresponding spatial scale probed by these fluxes is shown on the horizontal axis. See Chapter 2 for details.

bility data and the processed images are shown and compared to the results from the disc modelling.

1.6 THIS THESIS

With the recent advance in observational facilities in the submillimetre and the increased interest in the early stages in star and planet formation, the study of circumstellar discs over the last decade has grown substantially (e.g. Guilloteau & Dutrey 1994; Koerner & Sargent 1995; Qi et al. 2004; Piétu et al. 2005; Isella et al. 2007; Brown et al. 2007; Hughes et al. 2009). These studies focus on some key questions regarding the physical processes that involve both planet formation and the disc structure at a larger scale. For example, the very first stage of planet formation is the growth of dust to millimetre sized grains. This is the process that takes place in the dense disc mid-plane. The thermal dust emission at millimetre wavelengths increases as the grains grow and thus we see these discs bright in the millimetre. It will be very important in the coming years, with the advent of ALMA (see Section 1.6.8), to measure and spatially resolve the long-wavelength disc emission in order to quantify the grain growth ongoing in different disc regions. Another example is the later stage of planet formation, where the planets perturb the disc content. This process can cause gaps in disc gas and dust distribution or disc inner holes. Planet resonances can also cause disc material to clump and appear axially asymmetric. These features can be spatially resolved using a range of instruments.

The underlying theme throughout this thesis is the relative distribution of gas and dust in discs and consequently the main method used here are submillimetre interferometer observations sensitive to the disc density and temperature structure, both radial and vertical, resolved at scales ≥ 100 AU.

In this thesis, we address the following questions:

- How can we measure the gas mass in discs, and what constraints on the gas-to-dust mass ratio can be derived?
- How does the large scale (100 AU) disc structure probed with millimetre interferometry compare to the disc models based on the SED?
- Does disc modelling, based on the dust observations alone (SED, scattered light imaging, millimetre continuum imaging, silicate feature), provide a good description of the regions dominating the cold molecular gas emission?
- What are the typical temperatures and sizes of discs around intermediate-mass young (Herbig AeBe) stars and can we use these sources to measure disc gas masses?
- Should the SED be modelled from inside-out (starting from the near-infrared) or outside-in (starting from the submillimetre)?
- Can we derive reliable constraints on the stellar mass from the disc kinematics seen in submillimetric images of molecular gas?
- Can we test the radial drift models observationally?
- How can we probe the gas and dust spatial distribution in low-mass gas-poor discs at late stages of evolution?
- For what aspects of the study of disc mass and structure are submillimetre observations of gas essential?

1.6.1 Disc modelling approach proposed by this thesis

This thesis merges diverse observational methods to study disc structure, with a special focus on the submillimetre interferometry. Its complementarity with other observations, spatially resolved or not, is investigated in depth. Another important aspect of the work presented here is the joint analysis of dust and gas, in which the relative amounts and spatial distribution of these two components are investigated. The molecular excitation and radiative transfer code RATRAN (Hogerheijde & van der Tak 2000) is used throughout the thesis as an essential tool to model and interpret the molecular line emission arising from circumstellar discs. Figure 1.3 gives an overview of the methods and the observational constraints they provide. The methods are listed in a sequence designed to minimise the uncertainties in the analysis, with each method building on the input received from the previous one. The basic prerequisites for the modelling of disc structure are the constraints on the main geometric properties, the disc size R_{out} and inclination i , with which we can understand the extent and propagation of the emission better. As mentioned in Section 1.4, the best way to derive these parameters are the spatially resolved submillimetre interferometric observations of the rotational ^{12}CO emission. Where these are not available, other imaging methods sensitive to the outermost disc regions, like the scattered light, mid-infrared or fluorescent

H_2 imaging can provide some indication of R_{out} and i . The fluorescent H_2 imaging in the near-infrared is a surprising new observational method, discussed in Chapter 4. As shown in Chapter 5, even the ^{12}CO spectrum may be used to place constraints on R_{out} and i , thanks to the kinematic information it contains. In the same chapter we show that prior knowledge of R_{out} and i is essential for the SED modelling, otherwise the SED may be misinterpreted due to parameter degeneracy between i and the inner radius, and between R_{out} and the density distribution. Next step is the simple SED modelling, e.g., through comparison with the ‘ready-made’ SEDs in the D’Alessio et al. (2005) database of irradiated accretion disc models. The disc temperature structure can be assessed, particularly in the cold midplane regions, which are not directly illuminated by the central star and thus are less sensitive to the exact stellar radiation field and disc geometry. Given the midplane temperature structure at large (≈ 100 AU) radii, R_{out} and i , this is sufficient information for the interpretation of the spatially resolved interferometric observations of the thermal dust emission at millimetre wavelengths. In this way, the minimum dust mass can be derived and some information about the radial density structure can be obtained (see Chapters 2, 3 and 6). The detailed dust disc structure is derived in the following step, the simultaneous modelling of the SED, millimetre interferometric data, scattered light image and the silicate feature, probing, respectively, the inner disc, the outer disc midplane, the disc surface and the properties of the dust in the surface of the inner disc. The diverse observational constraints combined in this way allow to determine disc geometry, dust growth and settling as illustrated in Pinte et al. (2008). With the detailed knowledge of the dust distribution and properties, and in particular the disc temperature structure (dominated by dust), the three-dimensional structure of the disc main mass component, the molecular gas can be investigated through spatially resolved observations of ^{12}CO and isotopologue line emission as shown in Chapters 2 and 3. This approach has allowed us to go a step further than commonly done: in Chapter 2 we constrain the disc gas mass, while in Chapter 3 we find a striking discontinuity in disc structure that would not have been possible to identify without comparison between the gas observations and dust emission-based model. These models represent the most reliable description of the structure of the objects studied, and are a necessary input for testing of the physical and chemical processes heavily dependent on the disc density and temperature structure and the relative distribution of gas and dust.

1.6.2 Chapter 1

We investigate the three-dimensional structure of a gas-rich disc around the young star HD 169142 by observing the CO isotopologue rotational transitions of different optical depth with the Submillimetre Array interferometer. Our observations confirm the vertical and radial structure proposed by the SED model. The stellar luminosity is sufficient to heat the disc above the freeze-out limit (20 K) out to 150 AU in the disc midplane, nearly the full extent of the disc, and we estimate that the CO freeze-out affects only $\approx 8\%$ of the disc mass. Furthermore, photodissociation is negligible due to the sufficient dust mass and our result that the gas and dust are well mixed.

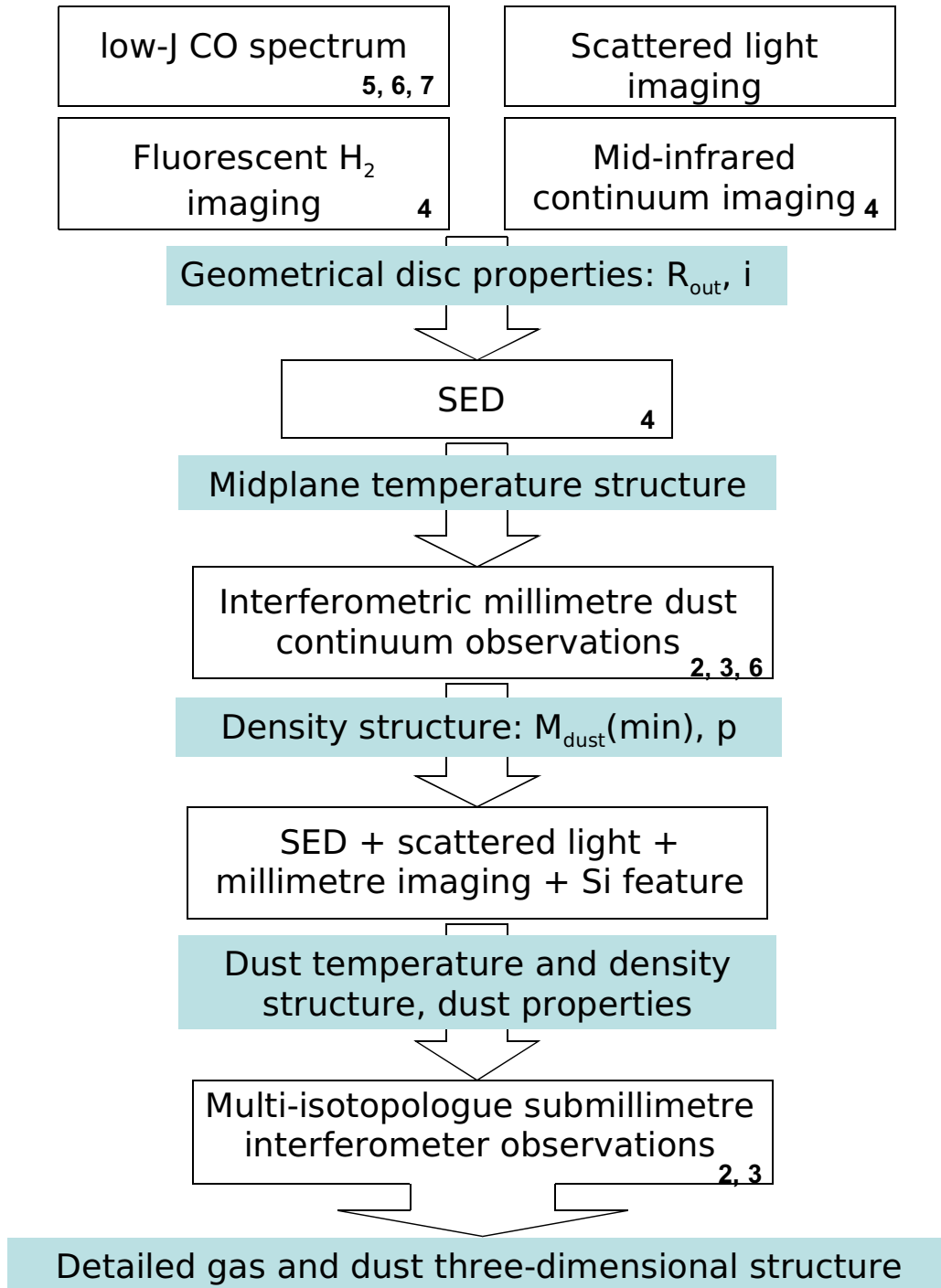


Figure 1.3: Recipe for disc modelling

This enables us to derive the disc gas mass of $(0.6-3.0) \times 10^{-2} M_{\odot}$ from our ^{13}CO and the optically thin $\text{C}^{18}\text{O } J=2-1$ line observations. The lower limit on the dust mass is $2 \times 10^{-4} M_{\odot}$, based on our 1.3 mm dust continuum data and the disc model. Our results, for standard dust opacities and molecular abundances, place the gas-to-dust mass ratio in this disc in the range 13-135. These unique constraints are facilitated by the small size of the disc around this A type star. We conclude that the small discs around Herbig AeBe stars are good potential targets for measuring the disc gas mass and in Chapter 5 we build on this result, concluding that the discs around Herbig AeBe stars are typically smaller than 200 AU. Chapter 5 also investigates whether the SED modelling produces a good base for modelling the low- J CO lines in discs in general.

1.6.3 Chapter 3

A similar approach as in Chapter 2 is used to study the structure of the disc around the young (T Tauri) star IM Lup. The SED model incorporates the constraints on the dust size and composition, dust settling, disc size and surface density distribution from a range of observations including the silicate feature, scattered light images and millimeter interferometry of the thermal dust continuum emission. Our ^{12}CO and $^{13}\text{CO } J=2-1$ interferometric images show the 900 AU large disc in Keplerian rotation around the central star. Because of the sufficiently high inclination ($i=50^\circ$), the stellar mass is well constrained by our observations to $1.2 \pm 0.2 M_{\odot}$, and is relatively insensitive to the exact disc inclination. The disc model based entirely on the dust emission does not trace the full extent of the disc, but merely the disc structure up to 400 AU from the star. We establish that there is a discontinuity in disc structure at 400 AU, with a notable drop in density of both gas and dust by a factor 10-100. The region at 400-900 AU has a very low density (H_2 column density $10^{20} - 10^{21} \text{ cm}^{-2}$) and temperature (10 K due to interstellar radiation field), and is therefore traced only with our CO submillimetre observations. The derived physical conditions in the disc and the estimated age of the star indicate that the dust radial drift combined with photodissociation of the gas is a plausible scenario to explain the observed low-density outer region in the IM Lup disc. A radial variation in the efficiency of angular momentum transport, resulting in a steep density profile, may trigger the drift process in the low-density outermost disc regions where the largest particles in the interstellar medium-like dust size distribution have the optimal drift size and contain most of the dust mass. Our results encourage studying very large discs for observational signatures of radial drift – the process that is believed to ultimately lead to accumulation of solid material in the regions closer to the star, up to densities sufficient for planets to form.

1.6.4 Chapter 4

We trace the circumstellar material associated with the weak-lined T Tauri star DoAr 21 by using, for the first time, the spatially resolved observations of the H_2 2.12 μm line emission with the SINFONI integral field spectroscopy unit on the Very Large Telescope (VLT). The inner 70 AU from the star are devoid of detectable amounts of H_2 , a

region found to be depleted of dust as well. The line emission arises entirely from a partial arc around the star at distances 70-200 AU. Warm dust imaging at $18\mu\text{m}$ with the VISIR mid-infrared imager on VLT, and some recent observations by other authors, confirm that this is the true distribution of the material, and that the disc is highly asymmetric. We investigate different scenarios in which this asymmetry may arise. Besides the possibility that the disc at the late stages of evolution has been severely perturbed, the observed emission may also come from material that has been gravitationally “captured” by the (diskless) star. Illumination of unrelated cloud material is a plausible scenario. Our results show that a young star with an SED indicative of a circumstellar disc with a large hole, must be imaged to confirm this hypothesis.

1.6.5 Chapter 5

As found in Chapter 2, the discs around Herbig Ae stars offer a possibility to constrain the gas mass when the disc is sufficiently small. Here, we study the spatially unresolved CO 3–2 line emission from a sample of Herbig AeBe stars from the literature, and the disc parameters probed by this emission: the disc radius, temperature and inclination. We use simple parametric disc models and find that the power law $T = 60 \times (R/100 \text{ AU})^{-0.5}$ provides a good description of the surface layers where the ^{12}CO 3–2 line is emitted. At $i \leq 45^\circ$ we can separate the contribution from the inclination and disc size to the line emission and profile, but for higher inclinations the two parameters are degenerate. We find that 75% of the observed sources have low line intensity and radii ≤ 200 AU. Therefore, the discs around Herbig AeBe stars are typically small enough to have the bulk of the CO in the gas phase, and observations of isotopologues like ^{13}CO and C^{18}O in these objects are sensitive to the total gas mass, unlike in the discs around T Tauri stars. Measuring the gas mass in these discs by using optically thin CO transitions may improve our understanding of the evolution of the disc gas content. For sources where SED models are available, we compare the CO 3–2 spectra calculated based on the models with the observations. We find that the SED modeling alone often leads to an underestimate of the disc outer radius, also seen in Chapter 3, and an overestimate of the inclination (especially in sources with inner holes). Because of this, the SED models generally do not provide a good description of the low- J CO spectra. Conversely, the spectral line fits provide useful estimates of i and R_{out} and should be taken into account when modelling the SEDs.

1.6.6 Chapter 6

We study the spatially unresolved interferometric observations of ^{12}CO $J=1-0$, ^{13}CO $J=1-0$ and HCO^+ $J=1-0$, as well as the dust continuum at 2.7 mm towards a sample of six discs around T Tauri stars. Disc size and inclination are available from previous, spatially resolved, observations. Simple parametric models, with the midplane temperature given by the SED models and power-law density structure with density scaled to fit the dust continuum flux, roughly reproduce the molecular line emission and are a good starting point for spectral line modelling and further modelling of the

disc structure, e.g. by fitting the SEDs. We derive minimum disc dust masses in the range of $(0.7-4.5) \times 10^{-4} M_{\odot}$ and, in some sources, evidence of substantial CO freeze out and/or photoevaporation.

1.6.7 Chapter 7

We analyse and model both low- J and high- J ^{12}CO line emission towards the disc around a Herbig Ae star HD 100546, observed using the Atacama Pathfinder Experiment Telescope at the resolution of 7-14". The dust emission from this source has been studied extensively over the past years and shows an intriguing disc structure, accompanied by an extended component. We identify the presence of significant amounts of warm gas associated with the disc at scales of 400 AU or smaller (half-size of the beam at 810 GHz). This is contrary to the late stages of evolution of the disc suggested by studies of its dust emission. The line profile is characteristic of a rotating disc of 400 AU in size seen at a 50° inclination. The observed asymmetry of the optically thick ^{12}CO lines may be due to asymmetry in the disc temperature, with one side of the disc colder than the other, possibly due to the obscuration of the outer disc surface by the warped inner disc suggested by previous work. We model the disc with a temperature asymmetry and obtain best fits for a 10-20 K temperature difference at 100 AU. A systematic mispointing by 1".9 in our different sets of observations can reproduce the line asymmetry, but is highly unlikely. Spatially resolved observations of this source, especially with ALMA in the future, are essential to characterise this puzzling source, one of the brightest discs of the southern sky.

1.6.8 Conclusions and future prospects

- A reliable estimate of the disc gas mass can be made based on the spatially resolved observations of optically thin rotational line emission of CO isotopologues in discs, when this emission is analysed in the framework of a well constrained disc structure model, and for discs where:
 - dust and gas are co-spatial radially and vertically, and
 - the midplane region between the radius where the temperature is 20 K and disc outer radius contains a minor fraction of the total disc mass.
- The discs around Herbig AeBe stars are typically small enough to have the bulk of their mass above 20 K, and thus freeze-out in these sources has a minor effect on the CO abundance (second condition of the previous conclusion).
- Molecular discs can extend beyond the disc regions that are optically thick in the near-infrared, and beyond the boundaries derived based on dust observations.
- Quiescent H_2 line emission at 2.12 μm can originate from circumstellar material located as far as 100-200 AU from the young star.

- Simplistic power-law disc models are a more efficient tool in the analysis of spatially unresolved submillimetre molecular line observations (spectra) than sophisticated models with a large number of free parameters.
- The modelling of the inner disc and the outer disc are interdependent. The “outside-in” disc modelling, starting from the spatially resolved submillimetre observations of gas and dust, is faster and more reliable than the SED modelling with or without additional constraints on disc large scale structure.

The future instrument of unprecedented sensitivity and spatial resolution in the submillimetre – the Atacama Large Millimetre Array will open new horizons for the studies of circumstellar discs. We will be able to discern smaller scale asymmetries, holes and gaps within the disc structure, that can be linked to planet-disc interaction. High spatial resolution will also allow to probe the radial distribution of the material better and in particular the dust emissivity. ALMA will be sensitive enough to image the submillimetre emission of low amounts of gas and dust in discs at later stages of evolution, a disc population that is just barely within reach of the current instruments but may provide an indication of the dissipation mechanism. Disc chemistry will be better constrained, through observations of molecular lines of a variety of species, many of which will be detected and resolved for the first time.

The recent launch of Herschel carries a promise of probing the far-infrared emission from discs, the region of the SED that has been lacking observational input. This wavelength regime is sensitive to disc geometry (flat or flared) and grain growth, and will allow us to probe them better. Last but not least, Herschel/HIFI will allow us to surmount the obstacle of water absorption by the atmosphere and search star-forming regions for water, the prerequisite for life.

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