Methanol masers and millimetre lines : a common origin in protostellar envelopes

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CHAPTER 1

Introduction

1.1 Star formation

Popular wisdom states that we are all made out of star dust, which to a very large extent is true, as all elements heavier than lithium have been formed in stars and supernovae in some way or another. But we can actually be a bit more specific than that; we are mainly made out of dust from stars more massive than our sun. Because the luminosity of a star depends on its mass $L \propto M^{3.5}$, the heavier the star is the hotter and faster it will burn. A star like our sun has a life expectancy of approximately 10 billion years, and our sun is now a comfortable 4.5 billion years old. As the universe is circa 13.7 billion years old, the material that makes up our sun (and solar system) cannot have had time to pass through a star such as our sun before forming our solar system. Most of the heavy elements around today must have formed in stars with shorter lifetimes and consequently more mass than our sun. In addition to enriching the Galaxy with heavier elements, the massive stars impact their local environment in at least two other ways: through their outflows, winds, and eventual supernovae they inject a large amount of mechanical energy in the interstellar medium (ISM). Furthermore their harsh uv-radiation ionises the environment. Also, when observing the powerful starburst galaxies, most of what we see is the intense radiation from the high-mass stars. All these reasons imply that high-mass stars are very important and understanding their formation is a key piece of the puzzle that makes up our universe (Zinnecker & Yorke 2007, Beuther et al. 2007a).

Most stars form in giant molecular clouds, dense interstellar clouds of tens of thousands to millions of solar masses, where most hydrogen is in the form of H_2 and with typical temperatures of 10 K. Inside the giant molecular clouds are clumps and filaments with the denser material called molecular clumps and dense molecular cores, Fig. 1.1. The cores are supported by the gas pressure (both thermal and non-thermal components) inside, working against the gravitational force. If the mass of the core is greater than the so-called Jeans mass, the internal pressure is not able to support the core and it will start to collapse. Depending on the size of the core and its internal dynamics the core may fragment into smaller cores. Another source of energy that is often ignored in models

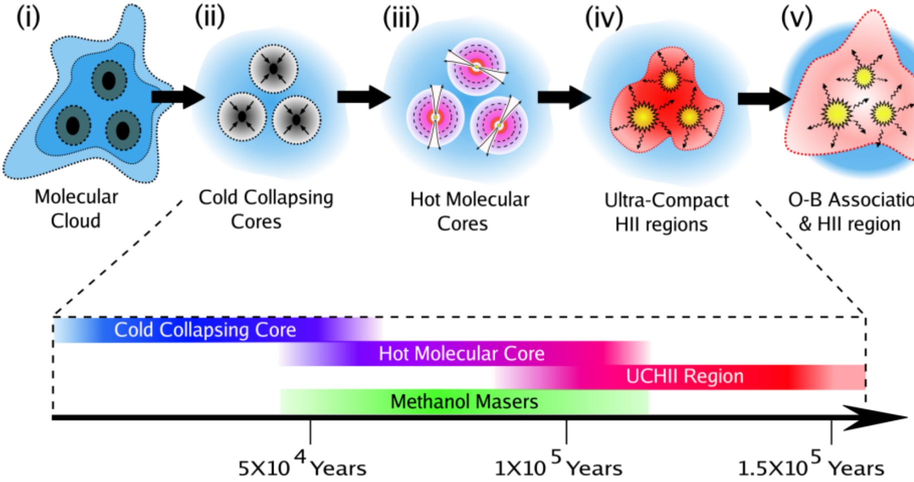

Figure 1.1: A cartoon of the early stages of high-mass star-formation, from molecular cloud to main sequence star. Also outlined are the time scales of the different phases and when the methanol maser emission supposedly occurs. Credit: Cormac Purcell.

of star formation is that of the magnetic fields. On large scales, the magnetic field can help support the cloud against gravitational collapse but also on smaller scales the magnetic field is important in regulating the feedback processes (e.g. Vlemmings et al. 2010). Also turbulence can be important, it affects the fragmentation of the cloud and can on small scales promote collapse. As the core collapses, gravitational energy is released as radiative energy, but the denser the core becomes, the more opaque it will get and when the gravitational energy can no longer be radiated away, the temperature of the core will increase. The protostar in the centre of the core will continue to accrete material and as the temperature increases through released gravitational energy and shocks, the dust in the dense part of the cloud will warm up and start to radiate thermal emission at mm and infra-red wavelengths. At some point the star will turn on and start to burn first deuterium and subsequently hydrogen and the accretion of material onto the star will stop. The star is then said to have reached the main sequence, where stars like our Sun spend billions of years, but massive stars only millions of years. The advent of the star turning on when it is still embedded in its natal core separates in a natural way the high-mass stars from their lower mass equivalents. In a first order approximation one can consider the gravitational collapse as spherically symmetric. In this case, as the star turns on, the radiation pressure will counteract the gravitational force and when the star reaches a mass of eight solar masses radiation pressure overcomes the gravitational force and accretion ceases (Eddington limit). However, stars with masses $> 200\ M_\odot$ have been observed and so they must be able to form in some manner (Crowther et al. 2010).

While low mass stars can form in relative isolation most stars form in groups or clusters, and many end up as binaries. It seems that more massive stars almost always form in clusters. The result of the clustered nature of massive star formation are open clusters that consists of tens of stars with combined masses of a few tens to hundreds of solar masses. The most well known example in the northern hemisphere is the Pleiades. The nature of high-mass star-formation has further consequences for observational astronomy. First of all the massive stars form in the densest part of the molecular clouds and they are therefore heavily obscured at optical wavelengths, so we are forced to turn to longer wavelengths, such as infra-red or radio emission. The longer wavelengths suffer from much less attenuation by the dust. Secondly, because of their short lifetimes and rapid evolution massive stars are far and few between. While the nearest low-mass star-forming regions can be found at a distance of $\sim$100 pc, the nearest high-mass star-forming region (Orion) is at a distance of 414 pc (Menten et al. 2007), and most regions are found at several kpc. The larger distances to the high-mass star-forming regions imply that the linear sizes become much larger for a given resolution compared with the low mass case. Also, because of the clustered nature of high-mass star-formation confusion is often a problem in that it is difficult to separate the different protostars and disentangle the —often multiple— outflows. All in all, these conditions make the observations of high-mass star-formation particularly challenging.

Several theories of how massive stars form have been proposed (Zinnecker & Yorke 2007, Beuther et al. 2007a). In the coalescence or merger scenario (Bonnell & Bate 2005) individual low- or intermediate-mass protostars merge to form higher mass protostars, requiring very high stellar densities. The two other scenarios, competitive accretion (Bonnell et al. 1998) and monolithic collapse or core accretion (McKee & Tan 2003) differ mainly in how a molecular clump fragments and how the high-mass protostar acquires its mass. In the competitive accretion scenario the clump fragments into low mass cores at an early stage and the individual cores then compete for the remaining unbound gas of the clump. Models have shown that this process has a very high star formation efficiency, and almost all gas is turned into stars. Although feedback processes that likely lower the star formation efficiency have not been included in the models, the observed star formation efficiency is much lower. Today, the most favoured scenario is that of monolithic collapse or core accretion. This scenario is basically an upscaled version of how low mass stars form, a core that has condensed from the larger molecular clump proceeds to evolve without much interaction (mass transfer) with other cores to form one or more stars. In this model it is proposed that a self-shielding, possibly magnetically controlled, accretion disk regulates the accretion beyond the Eddington limit. The stellar mass depends on the initial core mass as more massive cores would form higher mass stars. The result of this scenario is a relatively low star formation efficiency and a core mass function similar to the initial mass function (IMF) of stars, both of which are in good agreement with observations.

1.2 Molecular astrophysics

One of the diagnostics available when exploring the early stages of star formation are the radiative transitions of interstellar molecules. The first molecule to be detected in space was CH in 1937. In the 1960s and 1970s the field of molecular astrophysics really took off so that today, a mere 80 years after the discovery of CH, there are almost 170 molecules detected in space (see www.cdms.de for an up-to-date list). In particular, the rotational emission lines observable in the mm and sub-mm regime of the electromagnetic spectrum are valuable tools to explore the cold and dense regions of star formation, as the transitions are easily excited in cold environments and the longer wavelength radiation can penetrate through the dense clouds much more readily than radiation at shorter wavelengths. The spectrum of a molecule is determined by its internal structure and its dipole moment, but more than just identifying the molecule, the relative intensities of the different radiative transitions can be used to determine the physical conditions of the gas. Depending on the structure of the molecule one can constrain the temperature, column density, density and excitation of the gas. Symmetric rotors such as CH_3CN and NH_3 are particularly suitable probes of the temperature as several transitions can be observed within a single bandpass, whereas linear molecules such as CS, HCO^+, and HCN have traditionally been used as density probes (Evans 1999, van der Tak et al. 2007).

Gas in thermodynamic equilibrium is described by a single temperature, its kinetic temperature (T_k), which determines the energy level populations. However, in many astrophysical environments the conditions are such that the gas is not in thermodynamic equilibrium and therefore there may not be a single temperature that describes the excitation of the gas. The relative population of two energy levels is then described by what is called the excitation temperature (T_ex). Whether a particular transition is thermalised or not, depends on the balance of collisional (de-)excitation and the spontaneous emission coefficient (Einstein coefficient A_ul) of the particular transition. Therefore there exist for each molecule and transition a critical density for which collisions are more important than radiative processes. This mechanism populates the upper energy level, and the excitation temperature approaches the kinetic temperature. In contrast, in the low density case when collisions are not (or less) important the relative population is determined by the balance between collisional excitation and radiative decay. Also, stimulated absorption and emission can start to play a role, at the very least through the cosmic microwave background $T_\mathrm{rad} > 2.7\,\mathrm{K}$. If infrared radiation from warm dust is significant T_rad can be greater than T_ex (and even T_k), otherwise $T_\mathrm{rad} < T_\mathrm{ex} < T_\mathrm{k}$.

Another important factor that needs to be considered is the optical depth (τ_ν) of the lines. The optical depth describes the absorption coefficient or the detailed balance of radiative absorption (described by the Einstein coefficient B_{12}) and stimulated emission (Einstein coefficient B_{21}) of the gas. Another, perhaps more intuitive way to looking at the optical depth is as the interaction of the emitted photon with other molecules within a parcel of gas. In the case of optically thin emission the photon emitted by a molecule does not interact with any other molecule before escaping the parcel of gas. On the other hand, if the photon is absorbed by a molecule it will after a certain time be re-emitted in a random direction (isotropically). So, the higher the optical depth the more interactions of absorption and (isotropic) re-emission before the photon escapes the parcel of gas.

To analyse thermal emission from molecules a common assumption is that their excitation follow a Boltzmann distribution so that it can be described by a single temperature. Combined with the assumption that the lines are optically thin and that the emitting region is the same for all lines the temperature and column density of the gas can be determined

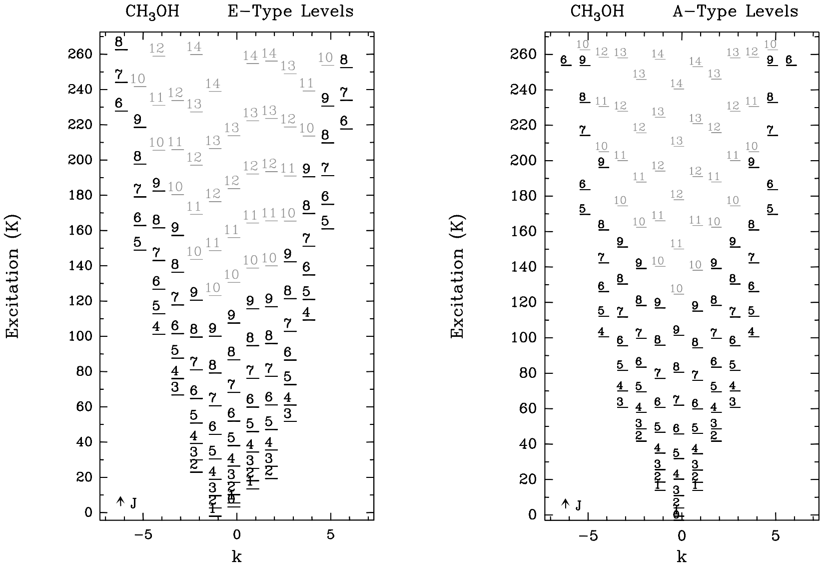

Figure 1.2: Energy level diagram of the CH_3OH E and A species. Credit: Silvia Leurini

by a least square solution to the relative populations of several pairs of the observed energy levels as measured by their respective line strengths, the so called rotation diagram analysis or Boltzmann plot (e.g. Helmich et al. 1994). Although this excitation temperature is not necessarily the same as the kinetic temperature, it provides a measure of the conditions in the gas. The analysis method can be extended to the population diagram method by including corrections for a finite optical depth and source size (Goldsmith & Langer 1999).

During the early stages of star formation a rich chemistry occurs, both in the solid phase in the icy mantles of dust grains, and in the gas phase (for a review, see van Dishoeck & Blake 1998). Also, complex molecules with ten and more atoms have been identified (Herbst & van Dishoeck 2009). The focus of this thesis is the CH_3OH (methanol) molecule and I will therefore limit the discussion to that species. CH_3OH was first discovered in the ISM in 1970 (Ball et al. 1970) and it was soon realised that the observed abundances could not be explained by gas phase chemistry only as the yields are too low. Subsequent studies have shown that the CH_3OH molecules are formed in the icy mantles of interstellar dust grains by hydrogenation of CO molecules at temperatures of $\sim$10 K (e.g. Fuchs et al. 2009). As the young protostellar object evolves and warms up its environment the CH_3OH molecules sublimate from the dust grains into the gas phase at $\sim$100 K (Collings et al. 2004). The CH_3OH molecule can be a great tool to explore the conditions of protostellar objects and their environments, if care is taken when selecting which transitions to study. It has closely spaced energy levels covering a wide

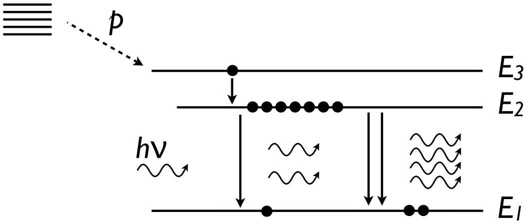

Figure 1.3: Schematic view of how maser emission occur. A pumping mechanism (p) supply the excitation to an energy state E_3 and the molecule then relaxes into the E_2 state. A photon with the correct energy can then stimulate the emission of a second identical photon.

range of excitation temperatures, Fig. 1.2. Due to its slight asymmetry it can serve as a probe of both the temperature and the density of the environment (Leurini et al. 2004). There are two distinct species of CH_3OH , A- and E type, determined by the symmetry of the molecule. Conversion between these two symmetry states is slow and for radiative transfer applications the two species can be treated as two separate molecules.

1.3 Masers

Microwave amplification by stimulated emission of radiation, or maser in short, is the equivalent of the laser for optical light, the difference being the longer wavelength of the microwave radiation. For maser action to occur in space requires at least three conditions to be met: the gas must be out of thermal equilibrium and a population inversion of the energy states must occur so that a higher energy state is over-populated, a seed photon of the wavelength corresponding to the maser frequency must be available, and sufficient amplification path length is needed (for a review, see Elitzur 1992). Affecting these criteria are several factors. First of all, the density must be below the critical density of the transition or the maser will be quenched by collisional de-exitation. Secondly, a pumping mechanism is required to sustain the population inversion, and depending on the type of maser, this can be either collisional or radiative pumping. To illustrate maser action consider a gas cloud made up of a molecular species with only three energy levels. In a simple three energy level system, $E_1 < E_2 < E_3$, the pumping mechanism would excite the molecules from the lower state E_1 to the higher energy state E_3 through (stimulated) absorption or collisional excitation. The molecule then relaxes into the E_2 state. Now, if the “half life” of the E_2 state is long compared to the pumping mechanism and the half life of E_3, more and more molecules will populate the E_2 energy state. A population inversion occurs with more molecules in the E_2 state than in the E_1 state. A seed photon with an energy $h\nu = E_2 - E_1$ passing through our imaginary gas cloud can then interact with a molecule in the excited E_2 state and stimulate the emission of a second photon. This second photon will be coherent to the first photon, meaning that it will have the same frequency, travel on the same direction and also have the same phase. These two photons can then stimulate the emission of two more photons and so on. The result is a shower of photons, coherent emission with the same direction, frequency, phase, and polarisation as the original seed photon. Another way to look at this is through the same analogy as with the optical depth above, but in this case a negative optical depth. So, when a photon of the energy $h\nu = E_2 - E_1$ interacts with a molecule in the excited E_2 state it is not absorbed but rather stimulates the emission of a second coherent photon. Maser emission is then the result of an exponential growth of interactions with molecules in the excited state.

Astronomical masers are made up of a large number of "individual" coherent masers and what we observe with our radio telescope is the emission resulting from an ensemble of masers, and therefore not necessarily coherent emission. Another consequence of the multiple masers is that they compete for the molecules in the excited state. So, if there is a preferred direction, such as a longer path length and/or a source of seed photons the individual masers along this direction will be preferential and depopulate the excited energy state so that maser emission in other directions will not be possible or at least much weaker. Such emission is said to be beamed. The path length of the maser then determines the maser intensity. The path length is determined by the length along the maser path through the gas cloud with a population inversion, but also with a velocity gradient smaller than the line width of the maser. Moreover, exponential amplification can only continue as long as the pumping mechanism can sustain the population inversion, when this is no longer possible the maser becomes saturated and the intensity no longer increases exponentially, but rather linearly with the path length.

The same CH_3OH molecules, when released to the gas phase, can also support bright maser emission, especially at the low energy cm transitions. The CH_3OH masers are divided into two different classes of spectral lines dependent on the pumping mechanism. Class I CH_3OH masers are supposedly collisionally pumped (Cragg et al. 1992). They are often observed in outflows of proto-stellar objects (Menten 1991a). In contrast, the class II CH_3OH masers are supposedly pumped by IR radiation (Sobolev & Deguchi 1994, Sobolev et al. 1997, Cragg et al. 2005) and are associated with the early stages of high-mass star-formation (Menten 1991a). In particular the 6.7 GHz CH_3OH masers, discovered as late as 1991 (Menten 1991b), have been found to be only associated with high-mass star-formation (Minier et al. 2003, Xu et al. 2008). But, more than just signposts of high-mass star formation, the high brightness temperatures of (CH_3OH) masers allows detailed high angular resolution studies with VLBI techniques (e.g. Norris et al. 1998) which can be used to determine their parallax (e.g. Reid et al. 2009a), internal motions, velocity fields, and even magnetic fields (Vlemmings et al. 2010). There is a still ongoing debate as to what physical structures the CH_3OH maser emission is associated with, in particular outflows and circumstellar disks are two of the main candidates (e.g. Minier et al. 2000, De Buizer 2003). A recent high-resolution study of 30 sources has revealed that ~30% have an elliptical distribution, suggesting a driving source in the centre (Bartkiewicz et al. 2009).

1.4 Radio interferometry

The resolution of a single dish telescope is limited to $1.2 \times \lambda/D$ radians, where λ is the wavelength, and D the diameter of the telescope. For example, the resolution of a 30-m telescope at a wavelength of 3 mm is $25''$. Studying objects at much higher resolution would require the construction of antennas with diameters of several 100 m, which is impossible. An alternative way to increase the resolution of radio frequency observations is to combine the signal from several telescopes and so synthesise a much larger telescope. This technique is known as interferometry, and by combining the signals of multiple telescopes the resolution is no longer limited by the diameter of the telescopes but rather the distance or projected baseline between the telescopes. In most interferometers the signals from several telescopes are combined and the instrument then becomes sensitive to emission that occurs on size scales between that corresponding to the minimum and the maximum baselines. Emission on large size scales is filtered out by the lack of short baselines and the maximum resolving power is limited by the longest baselines. The increase in resolution does however come at a price: although the sensitivity of the individual telescopes has not changed, the size of the emitting region has been dramatically reduced as the lack of short baselines filter out emission on larger size scales, and so the equivalent brightness temperature of the object must be much greater to be detected. In particular, for Very Long Baseline Interferometry (VLBI), non-thermal emission processes are required to produce high enough brightness temperatures $>10^6$ K to be detected (Thompson et al. 2001). What an interferometer does, is to sample the Fourier transform of the sky brightness distribution at the points in the $u - v$ (spatial frequency) plane determined by the baselines between antenna pairs. Limitations in the number of antennas and the available observing time lead inevitably to gaps in the sampling of the $u - v$ plane. In reality, through clever calibration techniques and by using an iterative deconvolution algorithm in combination with other image constraints one can reconstruct a model of the sky brightness distribution from the limited data points measured by the interferometer.

1.5 This thesis

The goal of this thesis is to study the relation between the 6.7 GHz maser emission, the protostar(s) responsible for the enhanced excitation and the thermal CH_3OH emission. Specific goals are to see whether we can determine where the CH_3OH maser emission arises in relation to the protostar and what the excitation conditions of the masing gas are. To do this we study a sample of 14 CH_3OH maser sources at different wavelengths and through different emission mechanisms. The sample contains some of the most nearby high-mass star-forming regions and was originally selected based on their close distances and infrared colour. Included in the sample are also three sources selected from the Toruń blind sample (Szymczak et al. 2000) for which high-resolution VLBI observations of the CH_3OH maser emission exists.

In Chapter 2 we present the results of European VLBI network (EVN) and very long baseline array (VLBA) observations of the 6.7 and 12.2 GHz CH_3OH maser emission towards Cepheus A HW2 (Cep A). In this chapter we also describe in some detail the calibration process used for all the VLBI data reduction. At a distance of 700 pc Cep A is the closest source in our sample, and one of the most well studied. The CH_3OH masers are distributed in a filamentary arc shape in the equatorial region of the protostar, perpendicular to the thermal jet observed at radio continuum wavelengths. The velocities of the individual maser spots suggest that infall is the dominant motion rather than rotation, although the multi-epoch observations do not show any significant motion of the maser spots. We argue that the CH_3OH masers occur close to, or in, a shock interface, between the actual accretion disk and the surrounding envelope of infalling material, a picture that fits with earlier polarisation measurements (Vlemmings et al. 2010).

The thermal CH_3OH observations of Cep A are presented in Chapter 3. The observations were performed with the HARP instrument, a heterodyne mixer with 16 pixels working at 345 GHz mounted on the 15 m James Clerk Maxwell Telescope (JCMT). We use this instrument to map the large scale distribution and excitation of the CH_3OH gas. The gas extends over $46''$ (0.16 pc) and a linear velocity gradient along the major axis suggests that the gas is entrained in an outflow. The large scale CH_3OH distribution has a low excitation with only a few lines detected at our sensitivity and temperatures of $\sim$50 K. In contrast, at the position of the HW2 protostar a second gas component is seen at a velocity similar to that of the maser emission. This second gas component is much more readily seen in the highly excited lines than in the lower excited lines. Whether this is due to optical depth effects or a population inversion, in either case it is clear that the second gas component is much more highly excited.

The same observational technique and methodology used in Chapter 3 has been applied to a sample of 13 sources associated with 6.7 GHz CH_3OH maser emission in Chapter 4. For eight of the sources in our sample (including Cep A) we characterise the thermal CH_3OH emission as compact. Four of the remaining sources have more extended thermal CH_3OH emission and more complex velocity fields, and in the last two sources the emission was too weak to be mapped. The compact sources all have a single peak in the intensity maps, close to the position of the CH_3OH maser emission. Furthermore, they have linear velocity gradients along the maser axis which we interpret as gas being entrained in an outflow. Also, in the rotation diagram analysis we find the highest rotation temperatures close to the maser emission. Although, in general, we do not detect many high-K lines, the detection of the $v_t = 1$ line towards half of the sources indicate the presence of highly excited gas. The population diagram analysis of the thermal CH_3OH emission at the position of the maser emission indicates that the optical depth of the lower-K lines is moderate. It is likely that the beam dilution is too large for the JCMT to probe the highly excited gas.

In Chapter 5, we present the results of a VLBI study of the 6.7 GHz CH_3OH maser emission towards the sources identified in Chapter 4 as having compact thermal CH_3OH emission. We have mapped the CH_3OH maser distribution towards three of the sources and include VLBI data on the maser distribution from the literature for an additional four compact sources. Although the VLBI observations typically only recover a fraction of the flux as measured by single dish observations, all spectral features in the single dish data can be recognised in the VLBI spectra. We therefore conclude that although the maser spots may be embedded in more extended emission, they still represent the entire physical structure. The maser spot distributions have extents of a few hundred to a couple of thousands of AU, in good agreement with what has been found in other studies. Furthermore, in three of the sources the masers appear to delineate, or be part of, a disk/torus in the equatorial region of the massive young stellar object (MYSO). The orientation of the disk/torus is perpendicular to the thermal CH_3OH emission observed in Chapter 4, supporting the argument that the thermal emission is entrained in an outflow. With the advent of ALMA it will be possible to probe the thermal gas on size scales similar to the maser emission for statistically significant samples of high-mass star-forming objects.

1.6 Main conclusions

We have found that for a fair fraction of the sources the methanol masers appear on size scales of ca. 1000 AU, in the equatorial region of the massive protostar. It appears that infall, rather than rotation, is the dominant motion. We propose that the maser emission occur close to or in a shock interface, possibly related to the accretion flow of the more extended gas in the protostellar envelope onto an accretion disk. The morphology and kinematics of the thermal CH_3OH gas support the hypothesis that the maser region is also the region where the CH_3OH molecules are released from the icy mantles of the dust grains. We have also estimated the temperature and column density of the CH_3OH gas in the outflows and find evidence for radiative excitation of the CH_3OH gas at the location of the maser emission. Our main findings are listed below.

- We detect thermal CH_3OH emission in all 6.7 GHz CH_3OH maser sources observed with the JCMT and in all but two of the sources we have been able to map the CH_3OH gas distribution and excitation.

- Half of the 6.7 GHz CH_3OH maser sources have compact thermal CH_3OH emission with a single peak in the integrated line flux maps. In these sources the thermal CH_3OH emission is centred close to the position of the CH_3OH maser emission.

- Several of the sources appear to have linear velocity gradients along the major axis of the CH_3OH emission suggesting that the CH_3OH gas is entrained in an outflow.

- The 6.7 GHz CH_3OH maser emission in half of the eight imaged sources is distributed in a disk/torus interface in the equatorial region of the massive protostars. The velocity field suggests that infall rather than rotation is the dominant motion.

- The disk/torus interface delineated by the maser emission appears to be oriented roughly perpendicular to the larger scale thermal CH_3OH emission of the envelope, supporting our argument that the thermal gas is entrained in an outflow.

- The detection of the CH_3OH $J = 7 - 6$ $v_t = 1$ line at 337.9 GHz in seven of the 14 sources indicates that radiative excitation is important at least in these sources.

However, the general lack of detection of high-*K* lines and consequently low rotation temperatures may be due to beam dilution if the region of highly excited gas is of comparable size as that of the maser emitting region, a few hundred to a couple of thousand AU.

1.7 Future prospects and outlook

The 6.7 GHz CH_3OH maser is an excellent signpost of the early stages of high-mass star-formation. Moreover the CH_3OH masers can be used to study these environments at very high angular resolution. Also, the specific conditions required for maser emission should tell us something about the physics of these sources. With this thesis we have a working hypothesis for a fraction of the maser sources. However, we still do not understand exactly which physical structures the maser emission trace in the remaining sources. It is also unclear whether the masers trace a mass range, a specific evolutionary stage or possibly both. There are several pathways to explore why, how and where maser emission occurs. In the following we will outline a few routes that seem particularly interesting given the recent upgrade and construction of new instruments with unique capabilities.

The 6.7 GHz CH_3OH maser does not seem to be associated with ultra-compact HII (UCHII) regions in general, as in most cases no radio continuum arising from free-free emission is detected towards the sources associated with masers. However, there may exist an earlier stage, a so called hyper-compact HII region in which the HII region is gravitationally trapped and the free-free emission optically thick also at millimetre wavelengths (Keto 2003). An optically thick HII region has a rising spectrum $S_\nu \propto \nu^2$ up to the turn-over frequency at which the region becomes optically thin. Because of the rising spectrum these regions are more readily detectable at higher frequencies (20-40 GHz). With the recent bandwidth upgrade of the eVLA from 172 MHz to 8 GHz the instrument has become seven times more sensitive and observations of large samples of CH_3OH masers are now possible. High resolution and astrometric accurate positions of the radio continuum is important to determine where the CH_3OH maser occurs in relation to the protostar(s) that are forming. Also, in the next few years, the SKA pathfinder MeerKAT promises to be a valuable tool to determine the association of HCHII regions and CH_3OH (12 GHz) masers in the southern hemisphere .

Mapping the thermal emission of molecular lines at high resolution towards more than a small handful of high-mass star-forming regions has up to now been impossible. The instruments capable of such observations such as the SMA and PdBI have not had the sensitivity to afford us to map larger samples of sources. With the advent of ALMA, a 66 dish interferometer built in the Atacama desert (Chile) at 5000 m altitude, this is changing dramatically. The high sensitivity combined with the high resolution capability of ALMA means that the thermal molecular line emission can be mapped on size scales comparable to that of the CH_3OH maser emission for statistically significant samples. If the CH_3OH maser emission arises in a disk or torus interface it will be possible to map and determine the excitation of the gas associated with the maser emission, and how it compares to the gas in the outflows and envelope.

Also, with continuing efforts of VLBI observations of CH_3OH masers of larger samples much can still be learned. Polarimetry allows us to probe the magnetic field on small scales close to the protostar but has only been done towards a couple of sources. With temporal monitoring and simultaneous observations of the radio continuum much more can be learned about the maser variability and apparent periodicity observed in some sources (Szymczak et al. 2011), in particular whether it is due to changes in the pumping of the maser or to intrinsic variability of the background source. Finally, through ongoing VLBI monitoring programmes, the parallax towards a significant number of high-mass star-forming regions have been measured. Not only does this provide an important independent distance determination to these regions, but it also gives important insights into the systematic motions within our Galaxy.