Molecular Environments of Class II 
Methanol Masers

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The average FWHM of the CS emission is found to be 4.3 kms$^{-1}$, the NH$_3$ (1,1), (2,2) and (3,3) transitions have line widths of 2.7 kms$^{-1}$, 3.1 kms$^{-1}$ and 4.6 kms$^{-1}$ respectively. The line widths of the NH$_3$ (1,1) emission suggest that the sources are at an evolutionary stage between massive protostellar collapse and the initiation of an UCHII region. The line widths of the NH$_3$ (3,3) emission are considerably larger than those of the NH$_3$ (1,1). This cannot be attributed solely to thermal broadening and may be indicating greater turbulence or more NH$_3$ (3,3) sub-structure along the line of sight. The sources with detected NH$_3$ (3,3) emission appear to be more turbulent than those sources without a NH$_3$ (3,3) detection.
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<td>GMC</td>
<td>Giant molecular cloud</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full width at half maximum</td>
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<tr>
<td>ISM</td>
<td>Interstellar medium</td>
</tr>
<tr>
<td>YSO</td>
<td>Young stellar object</td>
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<tr>
<td>MYSO</td>
<td>Massive young stellar object</td>
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<td>SED</td>
<td>Spectral energy distribution</td>
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<td>IRDC</td>
<td>Infra-red dark cloud</td>
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<td>UCHII region</td>
<td>Ultra compact HII region</td>
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<tr>
<td>HCHII region</td>
<td>Hyper compact HII region</td>
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<tr>
<td>EGO</td>
<td>Extended green objects</td>
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<tr>
<td>(V_{\text{LSR}})</td>
<td>Local standard of rest velocity</td>
</tr>
<tr>
<td>ATCA</td>
<td>Australian telescope compact array</td>
</tr>
<tr>
<td>ATNF</td>
<td>Australian telescope national array</td>
</tr>
<tr>
<td>MMB survey</td>
<td>Methanol multibeam survey</td>
</tr>
<tr>
<td>MOPS</td>
<td>Mopra Spectrometer</td>
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<tr>
<td>IF</td>
<td>Intermediate frequency</td>
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1

Introduction

1.1 Overview of Star Formation

The subject of how stars form has been an ongoing and debatable subject for many decades now (Spitzer 1949). Only relatively recently have we actually begun to fully understand the formation and evolution processes involved. The formation of low mass stars through gravitational collapse of an isothermal core, subsequently growing through accretion, is relatively well understood (Shu et al. 1987). However, we still do not understand the full paradigm of massive star formation ($M_\ast > 8M_\odot$) (Cesaroni et al. 2006) and as such remains a highly debated area. The field of star formation itself is of importance for the rest of the Galaxy and Universe. Star formation, especially massive star formation, plays a crucial role in the evolution of our Galaxy, producing a diversity of astrophysical phenomena such as black holes, pulsars and supernovae. Once formed massive stars severely disrupt the environment around them both initiating new generations of star birth but also destroying potential star forming clouds through their prodigious luminosity outputs. Massive stars are however extremely difficult to observe, due to their distance and rarity, but also the initial stages of star formation are extremely enshrouded in their natal dust and gas cores (Zinnecker & Yorke 2007) and are therefore optically obscured. This has lead to the need for other
signposts to be found that we can use to infer the properties of these regions. With the relatively recent technological advances we have begun to observe these regions in the millimetre/sub-millimetre and infrared. Molecular line emission from thermal and non-thermal maser species, could then be used as probes to the physical structure and the protostellar evolution of massive stars. It is then very advantageous to have an evolutionary picture of massive star formation, from the very initial stages of fragmentation within giant molecular clouds to the initiation of hydrogen burning, as these epochs will determine the eventual evolution of the parent cloud and the Galaxy on a whole. To do this we need to be able to link observational evidence to the evolutionary epochs involved in the production and formation of massive stars

1.1.1 Giant Molecular Clouds

Stars are born within molecular cloud complexes. These inhabit the diffuse interstellar medium (ISM), ranging in mass from a few to approximately $10^6 \ M_\odot$. The higher end of this mass range contains clouds which are termed giant molecular clouds (GMCs). These clouds consist predominantly of molecular hydrogen with sizes of the order 100pc (Lada 1999), and mean densities of $n(H_2) \sim 50 \ cm^{-3}$ (Blitz & Murdin 2000). GMCs are the most massive individual objects in the Galaxy. They are believed to form in the dense, turbulent environments of the Milky way's spiral arms (Ward-Thompson 2002). Formation is thought to be initiated through differential rotation in the Galactic spiral arms producing density waves that cause gravitational instabilities which in turn cause condensation in the most dense regions within the diffuse ISM (Ballesteros-Paredes et al. 2007). This is supported observationally as GMCs are seen to be constrained to the spiral arms of the Milky way (Stark & Lee 2005). GMCs are composed primarily of molecular hydrogen. The symmetric nature of this species produces a molecule that is observationally difficult to detect due to the lack of a dipole moment. The lower frequency rotational transitions of CO are more readily observed and have been used to infer the properties of GMCs (Dame et al. 2001). Initial results from
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the Herschel HiGal survey which can be seen in Figure 1.1 (Molinari et al. 2010), have revealed the ubiquitous filamentary nature of GMCs. It is difficult to place exact constraints on the properties of this fractal nature. (Williams et al. 2000) placed a hierarchical naming convention for the fragmentation within the clouds; where GMCs contain smaller structures termed “clumps” which in turn fragment and contain further sub-structure “cores”. This fragmentation system proposed for GMCs can be seen pictorially in Figure 1.2. Star formation in GMCs is very inefficient with only of the order of a few percent of the total mass of the cloud being converted into stars, additional effects such as magnetic fields or turbulence must then be supporting the cloud against local and global collapse. Turbulence is observed to be a ubiquitous feature within GMCs (McKee & Ostriker 2007), it is important on all scales supporting the GMC on large scales and assisting with the collapse of cores on the smallest scales (Ballesteros-Paredes et al. 2007). The large scale turbulence is generated by the Galactic rotation causing the initial fluctuations allowing the formation of GMCs, while intermediate turbulence is driven by supernova shock waves from massive stars, on the smallest scales stellar winds and outflows can produce turbulence.

The nature of GMCs and the sub-structure within them greatly influence the star formation and ultimately the nature of the stars formed, directly impacting the evolution of the cloud.

1.1.2 Low Mass Star Formation

The formation of low mass stars is relatively well understood. It is widely believed that low mass star formation occurs through the gravitational collapse of a dense prestellar isothermal core. The core becomes more condensed through the loss of turbulence, allowing gravity to dominate over the thermal and non-thermal pressure of the system initiating a free fall collapse. Within the standard model of star formation (Shu et al. 1987) the core is initially supported magnetically condensing through ambipolar diffusion. As the collapsing core is rotating conservation of angular momentum pre-
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Figure 1.1: Initial results from Herschel HiGal showing a $250\mu m$ field at $l=59^\circ$ which displays an interconnected maze of filaments with differing brightness throughout the ISM, the blue circles represent point sources at $250\mu m$ (Molinari et al. 2010).

Figure 1.2: Schematic showing fragmentation from diffuse HI regions down to dense protostellar cores (Schulz 2005).
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Figure 1.3: Schematic describing the relation between the protostar, circumstellar disc, and outflows (André et al. 2009), originally proposed by Machida et al. (2007)

vails and produces a centrifugally supported disc. Low mass stars then grow through the transportation of material through the accretion disc onto the central object (Shu et al. 1987). The accretion rate is not thought to be constant as predicted in the standard model, but believed to vary throughout the formation process with more rapid accretion occurring in the early stages (Larson 2003). The infalling matter that feeds the circumstellar disc also produces a highly collimated bipolar jet, the magnetic stresses in the accretion disc then launches the initial outflow (McKee & Ostriker 2007). Outflows are observed to be a ubiquitous feature of low mass star formation (Arce & Sargent 2006), the relation of the accretion disc, bipolar jet and outflow to the central protostar can be seen schematically in Figure 1.3.
1.1.3 High Mass Star Formation

The paradigm of massive star formation still remains a highly debated area. The evolutionary stages particularly the earliest stages in the production of a massive star and the extent to which a massive star can grow have been the subject of intense research for over a decade (Beuther 2011). The clustered and deeply embedded nature of massive star forming regions, make it difficult to disentangle the earliest stages in the formation process. High mass or massive stars are described as having a mass $>8M_{\odot}$ with the upper mass limit believed to be $150M_{\odot}$ (Figer 2005), however, recently Crowther et al. (2010) proposed that stars with mass greater than this upper mass limit have been observed. Understanding the environments and the formation process is observationally very difficult. One thing that is known about this elusive phenomena is that when massive stars do form they completely control the evolution of their environments.

High Mass Star Formation in Comparison to Low Mass Star Formation

Understanding the formation of massive stars $>8M_{\odot}$ is still a considerably more difficult task than the formation of low mass stars (Kahn 1974). It has been argued that high mass star formation cannot merely be modelled as a scaled up version of low mass star formation (Zinnecker & Yorke 2007). The nature of massive stars and the environments in which they form make them an observationally difficult phenomena to understand, unlike their low mass brethren they are typically at greater distances relative to us, form on shorter timescales, are rarer and begin burning hydrogen while they are deeply enshrouded in their natal cloud. Massive stars also form in dense clusters (Lada & Lada 2003), making it difficult to dissect the emission from a single massive protostellar object. Whereas low mass stars are known to also form in relative isolation at more favourable distances, making them observationally easier to study. The formation timescales of low and high mass stars is markedly different, and can be distinguished by the difference in their free fall and Kelvin Helmholtz timescales.

The timescale for a gravitationally bound cloud of gas and dust to collapse to a
central point is known as the free fall timescale, $t_{ff}$ (Equation 1.1), which represents the collapse when no opposing forces are apparent and the gravitational energy released does not affect the contraction. The freefall time is given by,

$$t_{ff} = \left( \frac{3\pi}{32G\rho} \right)^{1/2} = 3.4 \times 10^7 \, n^{-1/2} \, \text{years} \quad (1.1)$$

Where $G = 6.673 \times 10^{-11} \, \text{N.m}^2 \, \text{kg}^{-2}$ is the gravitational constant, $\rho$ is the average mass density in $\text{kgcm}^{-3}$ and $n$ is the number density in $\text{cm}^{-3}$. In typical molecular clouds $n \geq 50 \, \text{cm}^{-3}$ (Blitz & Murdin 2000) and the free fall time is $t_{ff} \leq 5 \times 10^6 \, \text{years}$, which gives a lower limit on the timescale for stellar evolution.

The Kelvin Helmholtz time $t_{KH}$, given in Equation 1.2 is an approximate timescale of which a protostar of a given mass could exist without the requiring the production of nuclear fusion in the core to sustain the luminosity.

$$t_{KH} \approx \frac{GM^2}{R_*L_*} \quad (1.2)$$

Where $R_*$ and $L_*$ are the stellar radius and luminosity respectively. Comparing $t_{KH}$ and $t_{ff}$ can give an insight into the evolution of a protostellar object. For a star where $t_{KH} < t_{ff}$ implies nuclear fusion has begun before the collapse has subsided, implying the stellar object will have reached main sequence while still forming. In comparison, when $t_{KH} > t_{ff}$ the protostar has ended its formation phase before reaching stardom.

When considering a 1 solar mass star similar to our Sun the $t_{KH}$ time is $\sim 3 \times 10^7 \, \text{years}$, when compared to the lifetimes of massive stars $\sim 10^5 \, \text{years}$. It is clear that for massive stars the $t_{KH}$ timescale is considerably shorter than for their low mass cousins.

This difference between low and high mass stars signifies an important difference between them in terms of their formation evolution. Massive stars are still deeply embedded in their natal cloud and still undergoing collapse and accretion when hydrogen burning has initiated in their core.

The luminosity of a star scales as $L_* \approx M_*^{3/4}$, therefore, clearly the more massive a star is the greater its luminosity will be. A major consequence of these factors is
such that the initiation of hydrogen burning while still in the protostellar phase produces prodigious energy output in the form of radiation pressure and photo-ionisation, which can greatly affect the accretion of material onto the protostellar object (Larson & Starrfield 1971). The accretion rates determined for low mass star formation are insufficient to describe the growth of massive stars given the timescale of their formation. These difficulties particularly those of feedback effects on massive stellar evolution have lead to several competing theories to explain how massive stars can accrete and reach the masses observed.

The three main theories that have been argued for the formation of massive stars are: monolithic collapse of a massive quasi-hydrostatic core (McKee & Tan 2003); competitive accretion (Bonnell 2008); (Bonnell & Bate 2006) and coalescence (Bonnell et al. 1998a).

1.1.4 Monolithic Collapse

The turbulent core model proposed by McKee & Tan (2003) uses the paradigm of low mass star formation (Shu et al. 1987), to envisage a theory for the formation of massive stars. The formation scenario involves the gravitational collapse of a massive core to form a massive protostar, that grows through the accretion of material from the infalling envelope. The accretion disc forms naturally through the non-zero angular momentum of the collapsing core. The accretion rates for massive star formation are required to be higher than the predicted accretion rates of $\sim 10^{-5} - 10^{-6} \, M_\odot \, yr^{-1}$ for low mass star formation. Considering also the effects of radiation pressure on massive star formation Tan & McKee (2002) suggest that accretion rates of $\sim 10^{-3} \, M_\odot \, yr^{-1}$ would be needed to produce massive stars in $\sim 10^5$ years. The geometry of the disc and the production of outflows are expected to channel radiation into the polar regions aiding the growth of massive stars (Yorke & Sonnhalter 2002), (Krumholz et al. 2009).
1.1.5 Competitive Accretion

Competitive accretion is the gravitational competition for gas within dense clusters. Fragmentation of the parent clump produces a cluster of mainly low mass protostars. Massive stars are then thought to grow through the continued accretion of material which is gravitationally channelled to the centre of the cluster through the system potential (Bonnell & Bate 2006) which can be seen schematically in Figure 1.4. The competitive accretion model then favours the production of massive stars toward the centre of clusters where the gas is being preferentially channelled through the system potential, this is in agreement with (Bonnell & Davies 1998) that massive stars are located in the centre of clusters. Unlike the turbulent core model the gas is not initially bound to the core, the central protostars grow through Bondi-Hoyle accretion. The initial fragmentation of the clump must be inefficient leaving a high content of gas that can then be available for accretion (Bonnell 2008), the gas must also be free and not magnetically frozen to allow efficient accretion. One of the major problems faced by
the competitive accretion scenario is again the effects of radiation pressure. Bondi-Hoyle accretion is found to suffer greatly, becoming inefficient for stars more massive than $10\,M_\odot$ (Edgar & Clarke 2004).

### 1.1.6 Coalescence

Coalescence was suggested to explain how the merger of two stars may possibly lead to the formation of an extremely massive star such as the Pistol star (Figer 2005). The advantage of collisional formation is that the feedback effects of radiation, that are so problematic in other formation models, are avoided (Bonnell et al. 1998b) and is consistent with the fact that massive stars form in dense clusters. Observationally and theoretically this formation hypothesis for massive star formation is believed to be the exception and not the rule. Observations of clusters do not reveal the high densities $10^6\,\text{pc}^{-3}$ and probably nearer to $10^8\,\text{pc}^{-3}$ necessary to allow collisions to prevail (Tan 2007). Baumgardt & Klessen (2010) performed N-body simulations showing that stellar collisions play a minor role, if any at all, concluding that formation through accretion is the most likely scenario.

### 1.2 Evolutionary Indicators

To form a complete picture of massive stellar evolution, from the very earliest cold, dense stages before collapse of protostellar cores to the initiation of hydrogen burning and star birth, it is invaluable to have indicators of differing stages of evolution. Having these evolutionary observational beacons would allow us to then probe the environments at varying epochs expanding our knowledge and understanding of the full paradigm of massive star formation.

A proposed evolutionary scheme for massive star formation begins with the fragmentation of a GMC into cold dense clouds termed Infrared dark clouds (IRDCs). These starless massive dense clouds will again fragment condensing to form deeply
embedded starless cores. The protostellar cores will begin to condense, as the central protostar begins forming and will begin to heat up the natal cloud. As the protostar grows along with the formation of an accretion disc the cloud will heat up to temperatures $\approx 100K$ forming a hot molecular core. The protostar will continue to grow reaching an evolutionary stage where its radiation is sufficient to ionise hydrogen and begin forming hyper and ultra compact HII regions (HC and UCHII regions). Eventually the radiation coupled with stellar winds and the outflows will disperse the enshrouding natal cloud allowing it to become optically visible. Throughout the vast majority of the evolution of a young stellar object (YSO) the central protostar is optically obscured by the surrounding gas and dust, so the existence of these proposed evolutionary stages has to then be inferred through other means.

1.2.1 Evolution of Young Stellar Objects

The evolution of a low mass star is observationally well understood and the evolutionary process for the formation has been divided into four classes (class 0, I, II and III). These classes are defined on the basis of their spectral energy distributions (SEDs) Lada (1987), Andre et al. (1993) and correspond to increasing black-body temperatures. The earliest stages of protostellar evolution class 0 and class I are enshrouded in the natal envelope and their SEDs are dominated by sub-millimetre and far infrared emission respectively. It is these initial stages where the young stellar object is believed to gain most of its mass. As the protostar evolves and begins to heat up the gas and dust envelope its emission tends towards shorter wavelengths termed class II. The gas and dust begins to dissipate allowing the central star to be observed in the optical, which is defined as class III in the YSO evolutionary scheme. Recently Molinari et al. (2008) concluded that this classification scheme remains valid when describing evolution of massive young stellar objects. However, due to the deeply embedded early stages and clustered environments that massive stars form in, it is difficult to disentangle the regions and relate the observations to a single massive protostellar objects.
Understanding the thermal and dynamical characteristics for massive stars at various evolutionary stages may aid in distinguishing if the SED distributions of massive star formation can be linked to that of low mass star formation, strengthening their formation process as an extension of low mass star formation.

1.2.2 Infrared Dark Clouds

IRDCs are believed to represent the earliest stages of massive star formation. Initially IRDCs were detected through mid-infrared surveys Perault et al. (1996), Egan et al. (1998), appearing as dark extended regions against the background emission. The characteristics of IRDCs were determined through their associated dust continuum and molecular line emission in the sub-millimetre regime. Through dust continuum observations Rathborne et al. (2006) IRDCs are found to have masses in the range $10^2$ to $10^4 \, M_\odot$. The temperature of IRDCs is typically $<20\,K$, with ammonia observations providing estimates of $17\,K$ (Pillai et al. 2006). IRDCs are large cold and dense structures ubiquitous throughout the galaxy. Sub-structure is seen throughout IRDCs, which is observed as higher extinction areas in the mid-infrared emission, which is likely due to enhanced column densities within these regions (Peretto & Fuller 2009). These IRDC fragments are approximately an order of magnitude smaller than their parent clouds and can range from $10M_\odot$ up to $1000M_\odot$ (Rathborne et al. 2006). The lower mass limit is of the order of a single massive star forming core whereas the higher mass limit is representative of massive protocluster masses (Lada & Lada 2003). IRDCs, therefore, likely represent the progenitors of massive protostellar and cluster formation, harbouring regions at the onset of collapse or at some initial stage in the process.

These dense and cold regions could then provide signposts of the very earliest stages of massive star formation. Providing an epoch to study the very initial processes involved in cluster and massive star formation that is often hindered by the turbulent phenomena associated with later evolutionary stages of formation such as winds and outflows.
1.2.3 Molecular Cores

Hot molecular cores are observationally very interesting as they produce a plethora of thermal and non-thermal molecular line emission in the sub-millimetre/millimetre regimes (Beuther 2007). The deeply embedded hot cores are believed to be precursors to UCHII regions (Churchwell 2002), forming before the central heating source(s) is sufficiently luminous to produce UCHII regions, distinguished by gas temperatures exceeding 100K (Kurtz et al. 2000). In the colder, denser prestellar core phase most molecular species will typically freeze out onto grains induced by the high density during collapse (van Dishoeck & Blake 1998). As the environment begins to heat up through the production of an accretion disc, initiating shocks and winds, the vast variety of molecular species are released from the ice mantles and the rich chemistry is revealed. The molecular emission provides a wealth of information, as species are prone to emit under certain physical conditions. The precursors to hot molecular cores would then be warm cores with gas temperatures $\leq 100$K and cold starless collapsing cores (Kurtz 2004). Understanding the emission can allow us to determine the temperature and density of the regions along with the gas dynamics. Potentially allowing us to place evolutionary constraints and understand the accretion and outflow processes of massive star forming regions.

1.2.4 HII Regions

HII regions are formed through the ionisation of hydrogen. To dissociate and ionise atomic and molecular hydrogen requires UV radiation with photon energies at the Lyman limit (13.6eV) or greater. Only massive stars are capable of producing radiation at the Lyman limit, the presence of an HII region is therefore synonymous with massive star formation (Hoare et al. 2007). HII regions are formed when the central protostellar object has sufficiently heated up its natal gas and dust cocoon. The natal envelope becomes optically thin to the UV radiation enabling its interaction with the surrounding ambient ISM. HII regions are then observed as expanding bubbles of ionised gas
and represent a relatively later stage in the evolution of a massive star forming region. They are extremely bright in the infrared due to the dust re-emitting the absorbed UV radiation as well as strong sources of radio continuum which arises through free-free emission. It is believed that UCHII regions represent the initial stages of ionisation, with diameters of $\leq 0.1\text{pc}$. More recently regions displaying a more compact ionisation structure with diameters $\leq 0.05\text{ pc}$ have been observed (Hoare et al. 2007). This new class of HII regions termed HCHII regions are believed to be pre-cursors to UCHII regions representing an earlier evolutionary stage in massive star formation.

The production of a HCHII region is thought to be initiated by the photo-ionisation of the accretion disc, with the onset of photo-evaporation producing a gravitationally constrained HCHII region (Zinnecker & Yorke 2007). The evolution of HII regions from HCHII to UCHII and the eventual larger scale HII region corresponds to an interesting transitional period; from protostar formation, through to the disruption of the envelope and the beginnings of main sequence life Churchwell (2002).

**Radiative Transfer**

Molecular line and continuum emission provide a means by which to infer the properties of the optically invisible, deeply embedded early stages of massive star formation. Radiative transfer describes the propagation of radiation through an isothermal medium. The radiative transfer equation describes how the intensity of the incident radiation is influenced when it passes through a medium such as a molecular cloud and is given by,

$$\frac{dI_\nu}{ds} = -\kappa_\nu I_\nu + j_\nu. \quad (1.3)$$

Where $I_\nu$ is the intensity of photons along our line of sight with a given frequency $\nu$. As the photons of a given frequency pass through an element of the medium of given volume $dAds$, they will suffer differing levels of attenuation depending on the nature of the region. The proportion of the original incident radiation, of intensity $I_\nu$ that is
attenuated is described by the absorption coefficient $\kappa_\nu$, which has units of cm$^{-1}$. The emission coefficient is given by $j_\nu$ and describes the energy emitted by the medium emitting within a solid angle $d\omega$ (Scheffler & Elsasser 1987).

**Optical Depth**

The optical depth $\tau_\nu$ given in Equation 1.4, is a measure of the attenuation of incident radiation along the line of sight and is dependent on the frequency of the radiation,

$$\tau_\nu = \int_0^S \kappa_\nu(s) ds.$$  \hspace{1cm} (1.4)

Values of $\tau_\nu \gg 1$ characterise a region which is deemed to be optically thick, implying that none or very little of the energy of the incident radiation of a given frequency can pass through the medium and reach the observer. For values of $\tau_\nu \leq 1$, the region is defined as optically thin and effectively the majority or all of the original radiation along the line of sight will pass through the given medium unaffected. When substituting the optical depth into Equation 1.3 and solving considering the optical depth concerning the whole region $\tau^*_\nu$ gives the relation,

$$I_\nu = I_\nu(\tau_\nu = 0) = I_\nu^0 e^{-\tau^*_\nu} + \int_{\nu}^{\tau^*_\nu} \frac{j_\nu}{\kappa_\nu} e^{-\tau_\nu} d\tau_\nu.$$  \hspace{1cm} (1.5)

**1.3 Outline of This Dissertation**

This Chapter has provided a brief introduction into massive star formation and discussed the proposed evolutionary stages. Chapter 2 will focus on masers in particular the 6.7 GHz Class II methanol maser and its association with massive star formation. Chapter 3 will explain the observations and data used in this dissertation describing the reduction methods and the sample selection. Chapter 4 will provide the results and the analysis of the molecular line observations reduced in Chapter 3 and Chapter
5 will discuss the results and analysis from Chapter 4. The following section briefly introduces the molecular line transitions that are analysed in this dissertation.

1.3.1 Molecules in This Thesis

CH$_3$OH

The methanol molecule (CH$_3$OH) has an extensive number of transitions, which can be seen in the thermal or non thermal (maser) emission. This work targets the massive star forming regions traced by the 6.7 GHz Class II methanol maser transition. A greater understanding of the structure and properties of the environments these sources inhabit is the aim of this thesis. Observations of the 44 GHz Class I methanol maser transition toward these regions are also obtained. These two transitions are discussed in more detail in Chapter 2.

CS

Mono-sulphide (CS) is known as a high gas density tracer and is therefore a useful probe of dense massive star forming regions. It is thought to be tracing the more quiescent extended region typically at an offset of $\sim$0.1–1pc from the central core (Anglada et al. 1996). Previous surveys using CS to study star forming environments include Anglada et al. (1996); Bronfman et al. (1996) and Zinchenko et al. (1998).

NH$_3$

The symmetric top structure of ammonia (NH$_3$) make it a useful tool to probe the temperature of star forming regions (Walmsley & Ungerechts 1983). The energy states of ammonia are denoted for each rotational transition in the form NH$_3$(J, K), where the letters $J$ and $K$ are quantum numbers representing the total angular momentum and the projection of the angular momentum along the molecular axis respectively Ho & Townes (1983).
The NH$_3$ (1,1), (2,2), (3,3) and (4,4) transitions originate from levels of 23, 64, 120 and 200K respectively above ground state and are typically collisionally excited (Ho & Townes 1983). It is possible to estimate the optical depth of the NH$_3$ (1,1) line using the brightness temperatures of the main and satellite components (denoted m and s respectively) of the hyperfine structure through the following relation (Ho & Townes 1983),

$$\frac{\Delta T_a^* (J,K,m)}{\Delta T_a^* (J,K,s)} = \frac{1 - e^{-\tau(J,K,m)}}{1 - e^{-a\tau(J,K,m)}}. \quad (1.6)$$

Where $\Delta T_a^* (J,K,m/s)$ is the observed brightness temperature of the main or satellite components and $\tau(J,K,m)$ is the optical depth of the main component. The value of $a$ represents the ratio of the intensity for the satellite to main components (Ho & Townes 1983). The NH$_3$ molecule can also be used as a thermometer and the NH$_3$ (1,1) and (2,2) transitions can be used to determine the kinetic temperatures of molecular clouds (Walmsley & Ungerechts 1983); (Tafalla et al. 2004) in regions where the gas is at temperatures of $\leq$30K (Danby et al. 1988).

Previous surveys using the NH$_3$ transitions to study the environments of massive star forming regions include (e.g. Pillai et al. (2006), Churchwell et al. (1990), Sridharan et al. (2002), Sridharan et al. (2005)). Sridharan et al. (2005) suggest that the line widths of the NH$_3$ (1,1) emission can be related to the evolution of the region, with broader line widths observed toward more evolved regions such as UCHII regions in respect to narrower NH$_3$ (1,1) line widths observed toward IRDCs.
1: INTRODUCTION
Masers and Massive Star Formation

Maser emission is a very useful tool in the study of massive star formation. Understanding the environments of the Class II CH$_3$OH masers is the main goal of this research. The following Chapter, therefore only briefly describes maser emission and the various molecular species that are known to have maser transitions. The majority of this Chapter is spent detailing the CH$_3$OH maser transitions in particular the 6.7 GHz Class II maser transition and its relation to massive star formation.

2.1 Masers

Maser emission is coherent, non-thermal emission at a particular frequency produced through a population inversion resulting in stimulated emission. A population inversion is created when molecules of the same species are “pumped” into an excited state either through collisional excitation or radiative pumping. The molecules will then de-excite through the most probable transition, producing a surplus of the molecules in a state which has a small probability of decaying resulting in a population inversion. Under certain conditions, which are strongly dependant on the environment, molecules can be stimulated to decay from this level resulting in the non-thermal maser emission observed. Maser emission has been observed in number of astrophysical regions from a variety of molecular species; these include water (H$_2$O), hydroxyl (OH), methanol
Figure 2.1: A schematic of the evolutionary time frame for different species of masers with some associated signposts of massive star formation (Breen et al. 2010).

(CH$_3$OH), silicon monoxide (SiO), formaldehyde (H$_2$CO), ammonia (NH$_3$) and acetaldehyde (CH$_3$CHO) (Fish 2007). Of these species the three most common and important in terms of studying massive star formation are water, methanol and hydroxyl. It is widely believed that all three are associated with varying evolutionary stages of massive star formation (Ellingsen et al. 2007). The most prominent maser transition is the 22 GHz emission from water (e.g. Babkovskaia & Poutanen (2004)), which is excited collisionally and is known to trace shocked regions, possibly tracing outflows from both young high and low mass stars (Furuya et al. 2001). The 22 GHz H$_2$O maser has, however, also been observed towards a variety of other astrophysical objects including planetary nebulae and is possibly tracing the jets or outflows of active galactic nuclei (Braatz et al. 2009). Hydroxyl masers are also seen in evolved stars as well as younger massive protostellar objects (Fish 2007). While the 6.7 GHz CH$_3$OH maser transition has the advantageous quality in terms of studying massive star formation that it is known to be associated with only young high mass star forming regions (Minier et al. 2003).

### 2.2 Methanol Masers

Methanol masers are split into two classes; originally this division was based on their apparent environment. Class A were observed at typically large offsets from known tracers of star formation, whereas Class B methanol masers were observed towards the
centre of star forming regions (Batrla et al. 1987). The criterion for the division was then refined by Slysh et al. (1994) to split the classes based on their differing excitation mechanisms. Class I (previously Class A) masers are found to be collisionally excited, while Class II (originally Class B) are radiatively pumped (Cragg et al. 1992), with both classes known to trace star formation (Menten 1991). The 6.7 GHz transition is the most prominent and well studied of the Class II methanol maser transitions. It is also exclusively associated with young massive star forming regions (Minier et al. 2003). The Class I transitions which include those at 25, 36, 44 and 95 GHz are believed to trace even earlier stages of massive star formation than Class II methanol masers (Ellingsen 2006). Figure 2.1 shows schematically this proposed evolutionary sequence of different maser species in relation to massive star formation (Breen et al. 2010), from the earliest stages to the production of an UCHII region. This however, is only an approximate evolutionary sequence, the overlap between species and the timescales between “switch on” and “switch off” still remain largely unclear. If an evolutionary sequence does exist, large unbiased surveys of the different maser species and their environments are required to provide constraints for the overlap periods between masers.

### 2.2.1 Class I Methanol Masers

The Class I maser is believed to form away from the central protostar ($> 10^4$AU) (Marseille et al. 2010), possibly created by the molecular outflow. Initiated through the interaction of the molecular bipolar outflow with the ambient ISM (Plambeck & Menten 1990), causing local density and temperature changes which produce the conditions necessary to mase (Marseille et al. 2010). A sample of sources surveyed in the 44 GHz transition by Kurtz et al. (2004) also show evidence of a strong correlation between this Class I transition and molecular shock tracers potentially attributed to the molecular outflow. More recently, targeted surveys of EGOs (extended green objects; which are massive young stellar objects with likely outflows traced by extended
emission in the 4.5 µm band (Cyganowski et al. 2008)) have found a strong correlation between these objects and Class I methanol masers indicating their association with outflows from young protostellar objects (Cyganowski et al. 2009) and (Chen et al. 2009).

Class I methanol masers are believed to trace the earliest stages of massive star formation (Ellingsen 2006). Pratap et al. (2008) suggest that the different transitions of the Class I maser may also be displaying a potential evolutionary sequence, surveying the 36 and 44 GHz Class I maser transition towards a sample of star forming regions Pratap et al. (2008) found the 36 GHz Class I masers to be tracing colder, less dense environments than the 44 GHz emission. They found that using a ratio of 5 for the 44 to 36 GHz emission line strength correlates with a possible evolutionary sequence. Objects having a ratio of the 44 to 36 GHz line strengths of >5 were found to correspond with regions believed to represent a more evolved stage than when the ratio of the 44 to 36 GHz emission was determined to be < 5, thought to be representing a colder less evolved state with no associated UCHII regions. Pratap et al. (2008) indicate from the results of previous models (e.g. Leurini et al. (2007), Cragg et al. (1992), Kalenskii (1995)) that CH$_3$OH masers in particularly the 36 and 44 GHz transitions display a strong temperature and density dependence with the 36 and 44 GHz lines peaking at estimated temperatures of 30–100K and 80–200K along with densities of $10^4$–$10^5$ cm$^{-3}$ and $10^5$–$10^6$ cm$^{-3}$ respectively. This suggests the possibility of an evolutionary sequence between Class I maser emission with the 36 GHz transition occurring typically at lower less evolved stages than the 44 GHz emission. Considering, however, the complexities in modelling maser emission and activity in star forming regions the models can only provide estimates for the temperature and density determinations.

2.2.2 Class II Methanol Masers

The two strongest Class II methanol maser transitions are at 6.7 GHz and the 12.2 GHz. The 6.7 GHz emission is known observationally and theoretically to produce the
brightest methanol maser emission (Sobolev et al. 2005), the second strongest emission of any maser species, with only the 22 GHz water line producing stronger emission (Ellingsen 2007). The 6.7 GHz methanol transition is one of the most commonly observed maser species, being the focus for a number of surveys and studies (e.g. Minier et al. 2003; Xu et al. 2008; Green et al. 2009). Exactly what mass range and evolutionary stage of star formation they trace was investigated by Minier et al. (2003). Surveying a sample of 175 low mass young stellar objects and prestellar cores for the presence of 6.7 GHz emission, Minier et al. (2003) found no 6.7 GHz emission, concluding that CH$_3$OH maser emission does not trace star forming regions with stars of mass $\leq 3M_\odot$. This result was also seen by Xu et al. (2008) when surveying 6.7 GHz maser emission towards H$_2$O masers; detecting no methanol masers towards low mass stars. Observationally Class II CH$_3$OH masers are not associated with strong radio continuum emission (e.g. Minier et al. (2005)). They are believed to exist in an earlier evolutionary stage before the formation of an HII region. This result has also been seen by Pandian et al. (2010), from a sample of 20 6.7 GHz CH$_3$OH masers 14 were not detected with any centimetre wave continuum with 6 being associated with either HC or UCHII regions. The Class II maser is also found to be variable, with observations showing periodicity and flaring in the emission of the 6.7 GHz and 12.2 GHz Class II maser transitions (e.g. van der Walt et al. (2009), Goedhart et al. (2008)). The 6.7 GHz CH$_3$OH maser is estimated to have a lifetime of $2.5\times10^4$–$4.5\times10^4$ years (van der Walt 2005). The 12.2 GHz maser has so far only been observed toward regions harbouring the 6.7 GHz CH$_3$OH maser and is typically less luminous, Breen et al. (2010) then infers the lifetime of the 12.2 GHz to be in the range and $1.4\times10^4$–$2.7\times10^4$ years, suggesting that the 12.2 GHz transition is “switched on” after the initiation of the 6.7 GHz maser and quenched while the 6.7 GHz maser is still active. Class II CH$_3$OH emission, particularly the 6.7 GHz transition, is an extremely useful signpost and tool into the field of early massive star formation. Understanding their spatial and evolutionary association to young massive star forming regions can greatly extend our knowledge of massive star formation.
2.3 Methanol Masers and Massive Star Formation

Unlike the Class I masers showing emission offset from the central region, the Class II masers are believed to be created close to the central protostellar object ($\leq 10^3$AU) (Marseille et al. 2010). The exact location and production of the emission in relation to the central protostellar core is not clear. Phillips et al. (1998) found through high resolution observations of the 6.7 GHz methanol maser transition towards 45 sources situated in the galactic plane, that 17 of the sources showed a linear or curved morphology and a velocity gradient along the line, concluding that the sources most likely traced edge on circumstellar discs. More recent work by Pestalozzi et al. (2009) also favour the differentially rotating disc scenario as the location of the Class II maser. In contrast to this hypothesis Bartkiewicz et al. (2009) and Torstensson et al. (2010) suggest that methanol masers form in a ring like structure finding an association between the CH$_3$OH emission and the disk torus interface, potentially initiated by a shocked region, but do not believe the emission is tracing the disc. Bartkiewicz et al. (2009) concluded through images in high resolution a sample of 31 6.7 GHz methanol masers, that their morphology and kinematics suggest the possibility that they are tracing either infall or outflow in this disc/torus interface. Torstensson et al. (2010) infer from observations of the star forming region Cepheus A that the Class I methanol maser emission is tracing the infall. It is possible that the location of the maser emission varies depending on the properties of the parent massive protostellar object. To understand fully the nature of disc structure around massive protostars and the association to maser emission, direct detections of the accretion disc, along with high resolution CH$_3$OH maser observations, would need to be achieved on a statistically complete sample. This would allow an insight into the formation mechanism of CH$_3$OH masers understanding if it is a homogenous process indigenous to massive stars or varies with environmental properties.
2.3.1 Class I and Class II Methanol Masers in Massive Star Forming Regions

The spatial coincidence of the Class I and Class II emission to the central star forming region and their association to an evolution timeline in massive star formation still remains unclear. The collisionally pumped Class I masers are believed to be produced when the local continuum radiation is lower than the gas kinetic temperature, whereas the Class II radiatively excited transitions dominate when the continuum radiation temperature becomes greater than the kinetic temperature of the gas (Cragg et al. 1992). Probing the thermal properties of the regions along with the related spatial coincidence of the Class I and Class II methanol masers could allow us to determine if a temperature dependence relationship does indeed exist and to what extent the classes overlap.

Unbiased surveys of the methanol maser classes would provide a statistically complete sample of massive star formation in various stages of evolution. Follow up molecular line analysis of the environments could allow constraints to be placed on the thermal and kinetic properties of the environments that these signposts trace, identifying if any of the properties differ with location in the Galaxy. Unbiased surveys of Class I masers have been completed over small regions and single clouds (e.g. Fuller et al. 2011; Pratap et al. 2008), however, no large unbiased surveys on galactic scales have been done as with the 6.7 GHz Class II maser transition (e.g. MMB survey, Green et al. (2009)). Fuller et al. (2011) observed a 0.97 square degree region of the galactic plane for 44 GHz CH$_3$OH emission. The region has been previously well observed and contains a high detection rate of Class II methanol masers from the MMB survey (32 in total were detected). In this region 23, 44 GHz Class I masers are detected, of these 26% are detected within 30'' of a 6.7 GHz maser source, which increases to 35% when expanding the spatial coincidence to include a Class I detection of up to 60'' from the 6.7 GHz Class II source positions. The detection rates of Class I masers toward Class II masers found by Fuller et al. (2011) differs substantially to the detection rates of Val'tts & Larionov (2007) who found 72% and Cyganowski et al. (2009) reporting an
89% detection rate. The sensitivity of the Cyganowski et al. (2009) survey is markedly higher, having a 6σ detection limit of 0.15 Jy for the Class I masers compared to the average Class I flux limit at 5σ, of 8 Jy used by Fuller et al. (2011). Cyganowski et al. (2009) also specifically target EGOs in their survey, likely introducing a bias into their detection rate, as Class I masers are known to trace outflows, in contrast to the likely lower detection rate expected in an unbiased sample. Val’tts & Larionov (2007) again find a higher detection rate of 72%, however they class a detection of up to 120″ which will be including a number of massive protostellar objects in the star forming region, increasing the likelihood of a Class I detection that may not be from the same protostellar object as the associated Class II maser emission.

2.3.2 Ammonia Toward Class II Methanol Masers

As described previously the inversion transitions of the ammonia molecule are an important tracer of the environments of massive star forming regions. Only a few surveys namely; Longmore et al. (2007a) and Wu et al. (2010), however, have specifically used ammonia to study regions of massive star formation traced by Class II CH$_3$OH maser sources.

Wu et al. (2010) use the NH$_3$ (1,1), (2,2), (3,3) and (4,4) transitions towards a sample of low and high luminosity 6.7 GHz Class II methanol masers to investigate if distinctions exist between the two groups. They found the higher luminosity masers to be typically more massive, with higher column densities than the low luminosity Class II masers. The NH$_3$ (2,2) line widths are found to be slightly broader than the NH$_3$ (1,1) line widths for both groups, however, the NH$_3$ (1,1) and (2,2) line widths are notably broader for the high luminosity masers compared to the smaller values found for the NH$_3$ (1,1) and (2,2) line widths in the low luminosity sample. As described in Section 1.3.1, Sridharan et al. (2005) suggest that the NH$_3$ (1,1) line widths can be an indication of the evolutionary stage of the region with broadening of the NH$_3$ line widths attributed to more evolved regions. Wu et al. (2010) also indicate a broadening
in the linewidths of the $^{12}\text{CO}$ 1-0 line which is thought to be tracing the outflow, in the higher luminosity masers. The NH$_3$ (1,1) and (2,2) transitions show strong correlation and are believed to be tracing the same regions of gas in the core, this result is also seen over the sample of sources surveyed by Longmore et al. (2007a), who find a similar morphology from the NH$_3$ (1,1) and (2,2) emission.

Longmore et al. (2007a) use the Australian telescope compact array (ATCA) to survey the NH$_3$ (1,1), (2,2), (4,4) and (5,5) transitions along with 24 GHz continuum emission toward 21 hot molecular cores traced by 6.7 GHz Class II methanol masers. The results indicate that the higher energy NH$_3$ transitions are tracing warmer gas as opposed to gas containing more ammonia. The association of 24 GHz emission and 6.7 GHz Class II methanol maser emission to the cores also reveals a potential evolutionary indicator of the central star forming regions (Longmore et al. 2007a). Follow up papers from this survey Longmore et al. (2007b) and Longmore et al. (2008), look more closely at this possible evolutionary sequence. They found narrower NH$_3$ (1,1) line widths in the quiescent cores with no Class II or associated continuum, compared to broader NH$_3$ (1,1) line widths in cores with Class II emission, with a further increase in the (1,1) line widths towards cores with both Class II and 24 GHz continuum emission. Longmore et al. (2007a) also found an increase in line widths toward higher energy NH$_3$ transitions, inferring that the line width broadening (which cannot be solely attributed to thermal broadening) may be indicating more turbulent gas or possible bulk motion of the gas such as rotation. The emission from the higher energy inversion NH$_3$ (4,4) and (5,5) transition are found to have a strong spatial coincidence with the Class II CH$_3$OH maser positions, implying that the Class II methanol masers are found in the warmer gas traced by the (4,4) and (5,5) ammonia cores.

Class II Methanol Maser and Ammonia Emission Towards Accretion Discs

Previous work by Cesaroni et al. (1998) and Beuther & Walsh (2008) have found that the higher energy NH$_3$ transitions are potentially tracing the accretion discs around massive star forming regions. With a high spatial resolution of 0.4 arcseconds, Beuther
& Walsh (2008) investigate the gas properties using the NH$_3$ (4,4) and (5,5) inversion transitions to better determine the kinematic and thermal characteristics of the gas. They find a possible rotating structure deeply embedded in the central core. The NH$_3$ (4,4) and (5,5) transitions are shown to trace the warm gas of the central core well and show a velocity gradient from east to west, perpendicular to the direction of the previously detected outflow. The resolution, however, does not permit direct detection of the inner accretion disc. The hyperfine structure is also not resolved but given the excitation temperatures of $\geq$ 200K for the higher energy transitions, gas temperatures in excess of 100K are expected (Beuther & Walsh 2008). Considering gas temperatures of 100K are predicted for accretion discs in the earliest stages of collapse (Krumholz 2006) it is possible that the NH$_3$ (4,4) emission could be tracing the accretion discs of massive protostellar objects.

The spatial coincidence of the NH$_3$ (4,4) and (5,5) emission with Class II methanol maser emission found by (Longmore et al. 2007a) and given that temperatures of $\geq$90K are sufficient to release CH$_3$OH from dust grains (Cragg et al. 2005) it is possible that the Class II maser emission is also tracing the warm gas close to the accretion disc. However, Beuther & Walsh (2008) have only investigated one high mass disc candidate and a larger statistically complete sample would be required to make any firm conclusions.
3

Sample and Data Reduction

3.1 Aim of This Work

The goal of this dissertation is to explore massive star forming regions traced by 6.7 GHz Class II CH$_3$OH maser emission to understand further and potentially constrain the properties of their environments. Deciphering if Class II maser emission is tracing a heterogeneous phenomenon or represents a homogeneous evolutionary stage ubiquitous with massive star formation. Along with trying to determine if their properties differ throughout the Galaxy. The suggestion of an evolutionary sequence between Class I and Class II maser emission is also an intriguing aspect that will be explored further. This dissertation uses a complete sample of 6.7 GHz Class II maser sources from the Methanol multibeam survey with follow up molecular line observations from the Parkes and Mopra telescopes. The sample contains a selection of sources chosen to probe the different spiral arms of the galaxy.

3.2 Methanol Multibeam Survey

The Methanol Multibeam Survey (MMB survey) is an unbiased survey of Class II CH$_3$OH maser emission over the Galactic plane. The first part of this survey was completed at Parkes in 2009 and covers the Galactic longitude from $0^\circ \rightarrow 60^\circ$ and
186° → 360° for |b| < 2° (Green et al. 2009). The second part of this survey plans to observe the Galactic longitude range from 60° → 176°, from the northern hemisphere. The survey has so far detected 850 Class II CH$_3$OH masers with over 300 of these new detections. Masers with new detections and those previously detected Class II masers without high resolution positional measurements were subsequently observed at high resolution with the Australian telescope compact array (ATCA). The MMB survey will therefore provide a complete census of young massive star formation taking place in our Galaxy (Green et al. 2009).

### 3.3 Sample Selection

From the MMB survey sources were selected for follow up observations, using the Parkes and Mopra telescopes. Due to time limitations it was not possible to observe all sources detected in the MMB survey with Parkes and Mopra. The follow up observations aim to explore the environmental properties of the Class II regions exploring any variance throughout the galaxy. A complete sample of 270 sources were selected to be observed in a number of spectral lines at Mopra and four ammonia transitions at Parkes. All the sample selection was observed at Mopra, however, due to time limitations only 215 of the 270 selected were observed at Parkes. These observations were undertaken and completed at Parkes and Mopra in March and April 2010 respectively. To look for evidence of variance in the environments over the galactic plane the sources were selected to sample the different spiral arms of the Galaxy. Table 3.1 shows the number of sources observed over the given longitude ranges and the spiral arms they sample.

### 3.4 Mopra Survey

Follow up observations of 270 sources from the MMB survey were completed in 2010 using the 22m diameter Mopra telescope. The Mopra telescope, which is part of the
Table 3.1: Number of sources observed at Mopra and Parkes over given longitude ranges of the Galactic plane.

<table>
<thead>
<tr>
<th>Region</th>
<th>Galactic range (Degrees)</th>
<th>Number of sources observed with Mopra</th>
<th>Number of sources observed with Parkes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centaurus tangent</td>
<td>305 → 315</td>
<td>53</td>
<td>52</td>
</tr>
<tr>
<td>Norma tangent</td>
<td>335 → 340</td>
<td>85</td>
<td>78</td>
</tr>
<tr>
<td>Scutum tangent</td>
<td>20 → 35</td>
<td>72</td>
<td>50</td>
</tr>
<tr>
<td>3 kpc arm</td>
<td>345 → 0 → 15</td>
<td>50</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>40→50</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>

Australia Telescope National Facility (ATNF)\(^1\), was configured to observe over a frequency range 42 GHz to 50 GHz, simultaneously observing 15 molecular emission lines. This range includes the CS \(J=1-0\) transition at 48.990957 GHz which is a useful dense gas tracer and the 44.069476 GHz \(7_0 \rightarrow 6_6\) \(A^+\) Class I CH\(_3\)OH maser transition. The resolution of a single dish telescope is given in Equation 3.1:

\[
\theta = \frac{1.22\lambda}{D}.
\]  

(3.1)

Where \(D\) is the diameter, \(\lambda\) is the wavelength observed and \(\theta\) is the resolution. For the observations done at Mopra this gives a resolution or beam size of \(\sim 1'\). The Mopra spectrometer (MOPs) was configured with 15 intermediate frequency (IF) spectral windows. Comprising of a bandwidth of 138 MHz and a channel width of 33.7 KHz, which gives a total velocity coverage of \(\pm 200 \text{ kms}^{-1}\) and channel width of \(\sim 0.25 \text{ kms}^{-1}\) for each spectral line. A list of the molecular species simultaneously observed along with their corresponding IF and rest frequency is shown in Table 3.2. The sources were observed in position switching mode. This pointed mode of observation, consists of observing the actual target source (the pointing was centered on the MMB coordinates) and then pointing at an emission free position. Subtraction of the emission

\(^1\)http://www.atnf.csiro.au/
Table 3.2: Rest frequencies of the 15 molecular species observed using the Mopra telescope. The related IFs are also provided.

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Rest frequency (GHz)</th>
<th>IF</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC$_3$N</td>
<td>42.215590</td>
<td>0</td>
</tr>
<tr>
<td>HCS$^+$</td>
<td>42.674192</td>
<td>1</td>
</tr>
<tr>
<td>SiO</td>
<td>43.122090</td>
<td>2</td>
</tr>
<tr>
<td>SiO</td>
<td>43.423853</td>
<td>3</td>
</tr>
<tr>
<td>HNCO</td>
<td>43.962998</td>
<td>4</td>
</tr>
<tr>
<td>CH$_3$OH (Class I maser)</td>
<td>44.069476</td>
<td>5</td>
</tr>
<tr>
<td>HC$_3$N</td>
<td>45.490319</td>
<td>6</td>
</tr>
<tr>
<td>HC$_3$N (Vibrational)</td>
<td>45.602171</td>
<td>7</td>
</tr>
<tr>
<td>$^{13}$CS</td>
<td>46.247568</td>
<td>8</td>
</tr>
<tr>
<td>C$_3$H$_2$</td>
<td>46.755614</td>
<td>9</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>47.913426</td>
<td>10</td>
</tr>
<tr>
<td>C$_3^{34}$S</td>
<td>48.206941</td>
<td>11</td>
</tr>
<tr>
<td>H$_2$CO</td>
<td>48.284522</td>
<td>12</td>
</tr>
<tr>
<td>OCS</td>
<td>48.651604</td>
<td>13</td>
</tr>
<tr>
<td>CS</td>
<td>48.990957</td>
<td>14</td>
</tr>
</tbody>
</table>

Free signal from the target signal will then remove any instrumental and atmospheric contribution leaving the only the true emission from the target source. The atmosphere can fluctuate over timescales shorter than 15 minutes. To reduce noise incurred from these fluctuations, one full pointing was observed for 16 minutes, 8 minutes on source and 8 minutes in the off position with 2 minute intervals. The 15 residuals are then subtracted and averaged to provide the final spectra. At the beginning of each observing run and then approximately hourly, the telescope pointing was checked using SiO maser sources. The pointing was typically found to be offset <7".
3.4: MOPRA SURVEY

3.4.1 Reduction of Mopra Observations

The 15 residuals taken for each source were subtracted and averaged in ASAP\(^2\). ASAP is a spectral analysis package provided by the ATNF, it has been specially designed to reduce single dish, spectral line pointed observations. In the reduction of the data the frequency frame used is the local standard of rest \(V_{\text{LSR}}\), the velocity units were set to \(\text{kms}^{-1}\) and the frequency was set to GHz. ASAP provides baseline and gaussian fitting routines, they work by masking a region of the spectrum over which the baseline or fit is to be made. The spectra of the 15 molecular lines observed at Mopra are shown in Figure 3.1. The IFs and the molecular species they correspond to is given in Table 3.2. From the observations at Mopra the CS J=1-0 and the Class I CH\(_3\)OH maser transitions are the only species investigated in this dissertation. The typical rms noise levels of the CS and 44 GHz CH\(_3\)OH spectra were found to be \(\sim 0.05\)K and \(\sim 0.03\)K respectively.

3.4.2 CS Reduction

To fit the CS emission an initial single Gaussian fit was performed over the whole spectrum \(\pm 200 \text{ kms}^{-1}\) to search for the main peak of the emission and the corresponding velocity of this peak. The initial fits were then inspected manually to detect any extra components in the emission spectrum. All components found manually were then separately fitted with a Gaussian. The velocity from the first single Gaussian fit was used to determine the mask region, providing a mask around the original main spectral emission component. The mask is set over two regions with the limits determined by \(V_{\text{LSR}} \pm 7 \text{ kms}^{-1}\) and \(\pm 40 \text{ kms}^{-1}\). This mask was then used to fit a third order polynomial to the selected region of the spectra and then subtracted from the spectra. The main component (ncomp=1) was then fitted with a Gaussian again using this mask. The emission lines of the other components termed ncomp=2, ncomp=3 and so on were then reduced in the same way as ncomp=1, only the mask region was determined using the manual estimations of their peak velocity through the visual inspection of

\(^2\)http://svn.atnf.csiro.au/trac/asap
Figure 3.1: The spectra of the 15 molecular lines observed at Mopra. The spectra display the calibration source Iras 17233 which has Galactic coordinates G351.7730 -0.5360. The spectrum at the top left hand of the image corresponds to IF 0, working from left to right the IFs increase numerically. The molecular transitions the spectra correspond to is given in Table 3.2, not all of the spectra have been reduced and baselined.

The final Gaussian fits for all components were then put into a database. The fit parameters provided from the single gaussian fit are the peak intensity (K), the velocity at this peak (kms$^{-1}$) the FWHM (kms$^{-1}$) their associated errors and the rms of the baseline. The peak intensity given as a brightness temperature (K) can be converted to a flux measurement in units of Jy using the conversion factor 13.4 (Urquhart et al. 2010). Any spectra in which a Gaussian could not be fitted, were baselined as above, but were manually fitted using an interactive fitting tool. A selection of the sources were observed more than once, due to bad weather or problems with observations. These sources were inspected and the spectra with the least noise or corruption were
Figure 3.2: A selection of three Class I maser spectra showing the typical structure of Class I maser emission. Included are two calibration sources Iras 17233 (G351.7730-0.5360) and W51e1 (G49.4900-0.3870). The third source is taken from the source sample (G20.7334-0.0594) the properties of the fit for this source can be seen in Table 4.6.

3.4.3 44 GHz Class I Methanol Maser Reduction

The nature of maser emission produces an emission spectra which typically has a high intensity very narrow spike, with many of the spectra also showing an associated less intense broad structure, this can be seen in Figure 3.2. This emission is then difficult to fit with a Gaussian, as the extended structure is not accurately accounted for and the peak intensity is typically underestimated. The 44 GHz lines were similarly reduced and averaged in ASAP. The baseline of the spectrum and parameters of the spectral line were determined using an interactive spectral line tool in conjunction with ASAP.
Figure 3.3: Spectra of one of the calibration sources W51e1 (G49.4900-0.3870). The top left panel displays the NH$_3$ (1,1), (2,2) and (3,3) spectra taken from ASAP prior to being reduced and baselined. The top right panel displays the spectrum of the observed NH$_3$ (1,1) emission and clearly shows the associated hyperfine structure. The bottom left and right panels are the spectra of the NH$_3$ (2,2) and (3,3) emission respectively.

The lower velocity and higher velocity limits were determined visually by interactively selecting the lowest and highest velocity associated with emission structure. The peak brightness temperature and the velocity corresponding to the velocity range selected are then determined. The fit parameters determined are the peak intensity, the velocity at this peak, the lower and higher limits of the emission structure, and the rms of the baseline.
3.5 Parkes Survey

The Parkes 64m diameter telescope is also part of the ATNF. Using the Parkes telescope 215 of the 270 sources selected from the MMB survey were simultaneously observed in the NH$_3$ (1,1), (2,2), (3,3) and (4,4) metastable inversion transitions. The frequency and bandwidths used for the four transitions is shown in Table 3.3. At the frequencies observed and given the Parkes dish diameter of 64m, this gives a resolution or beam size for the observations of $\sim 40''$. The observations were done in a similar manner to the Mopra data, with pointed observations on and off source, spending a total of 16 minutes per observation corresponding to 8 minutes on source and 8 minutes off source. The observations were again calibrated approximately every hour for positional offsets, with sensitivity calibrations done on known calibration sources at the beginning of each session. The typical rms noise values were found to be $\sim 0.03$Jy for the NH$_3$ (1,1), (2,2) and (3,3) transitions. The typical structure of the emission for the NH$_3$ (1,1), (2,2) and (3,3) transitions is shown in Figure 3.3.

3.5.1 NH$_3$ Reduction

The residuals for each source were then subtracted and averaged in ASAP as with the Mopra data. Due to time limitations only the NH$_3$ (1,1), (2,2) and (3,3) transitions were reduced and baselined, again using the single dish spectral line analysis tool ASAP. To determine the mask region to perform the baseline, an intial Gaussian fit was made to the NH$_3$ (2,2) line (the hyperfine structure of the NH$_3$ (2,2) emission is not resolved by the resolution acheived with Parkes and is therefore not as prevalent in the NH$_3$ (2,2) compared to the NH$_3$ (1,1) emission). Again the mask was set over two regions given as the NH$_3$ (2,2) velocity peak $\pm 7$ kms$^{-1}$ and $\pm 40$ kms$^{-1}$. The baselined spectra were then converted to fits files which can be used in CLASS (which is part of the GILDAS software package 3). As the ammonia transitions have a hyperfine structure (which can be seen clearly in the (1,1) transition in Figure 3.3) multiple gaussians must be fit

3http://www.iram.fr/IRAMFR/GILDAS
simultaneously to the main and satellite components. CLASS is a single dish spectral line analysis software package that provides routines capable of fitting the hyperfine structure of the NH\textsubscript{3} (1,1), (2,2) and (3,3) emission. The spectra are again baselined in the CLASS procedure with the masking region determined from the estimate of the NH\textsubscript{3} (2,2) velocity found in the ASAP gaussian fit. Using the NH\textsubscript{3} (2,2) \(V_{\text{LSR}}\) to fit the NH\textsubscript{3} (1,1) and (3,3) emission should provide a reasonable estimate of their peak velocities as they are believed to be from the same region and should have a very similar \(V_{\text{LSR}}\) structure. Any sources which did not fit using this \(V_{\text{LSR}}\) were fitted manually in CLASS, these sources were found to have weak emission with some part of the noise incorrectly fitted. Velocity estimates from the CS emission for these sources were then used to baseline and refit the spectra.

The CLASS NH\textsubscript{3} fitting method provided by CLASS fits each of the hyperfine structure of the ammonia transitions with a gaussian distribution. Providing four parameters of the fitted structure; (1) the product of the main group opacity with that of the excitation temperature minus the background temperature, (2) the velocity of the main component, (3) the line width of the main component (which is the FWHM of a single hyperfine component accounting for line broadening from optical depth effects and the velocity dispersion in the main component due to spectrometer resolution ) and (4) the main group opacity, along with the rms of the baseline and the line. To fit the structure using method NH\textsubscript{3}, CLASS assumes that the hyperfine components have equal excitation temperatures and velocity dispersions (Longmore et al. 2007a). The optical depth \(\tau\) which was introduced previously in Section 1.2.4 is automatically calculated by CLASS (parameter (4) the main group opacity). To convert the peak fluxes given in Jy to brightness temperatures a conversion factor of 3.5 is applied.
Table 3.3: Properties of the NH$_3$ transitions, the rest frequencies along with the bandwidth and channel width are provided.

<table>
<thead>
<tr>
<th>Transition</th>
<th>$\nu_{\text{rest}}$</th>
<th>Bandwidth</th>
<th>Channel width</th>
</tr>
</thead>
<tbody>
<tr>
<td>NH$_3$(1,1)</td>
<td>23.6944955</td>
<td>256</td>
<td>$\sim$ 31.5</td>
</tr>
<tr>
<td>NH$_3$(2,2)</td>
<td>23.7226336</td>
<td>256</td>
<td>$\sim$ 31.5</td>
</tr>
<tr>
<td>NH$_3$(3,3)</td>
<td>23.8701296</td>
<td>256</td>
<td>$\sim$ 31.5</td>
</tr>
<tr>
<td>NH$_3$(4,4)</td>
<td>24.1394169</td>
<td>32</td>
<td>$\sim$ 8</td>
</tr>
</tbody>
</table>
3: SAMPLE AND DATA REDUCTION
4

Results and Analysis

The main goal of this research is to explore the environments of massive star forming regions traced by Class II CH$_3$OH maser emission. From the observations undertaken at Mopra and Parkes, described in Chapter 3, the properties of the CS, Class I CH$_3$OH maser emission and the NH$_3$ (1,1), (2,2) and (3,3) transitions, are explored and analysed in the following Chapter.

4.1 Overview of Data and Previous Surveys

The number of sources for each molecular species investigated in this research is summarized in Tables 4.1, 4.2, and 4.3. Table 4.1 provides details of the sources observed at Mopra in the CS and Class I CH$_3$OH maser transition, Table 4.2 describes sources observed at Parkes in the NH$_3$ (1,1), (2,2) and (3,3) transitions and Table 4.3 is a comparison of sources observed with both Mopra and Parkes. All sources have 6.7 GHz Class II maser emission from the MMB survey. All the sources observed at Parkes in NH$_3$ were previously observed at Mopra and have corresponding CS and 44 GHz Class I maser emission. Due to time limitations at Parkes not all sources in the sample were observed and as such the the sample size of the Parkes data is smaller. In total 270 sources were observed at Mopra of these 247 had CS emission detected at $3\sigma$ or greater (where $\sigma$ is the rms noise in the spectra), while 216 of these had CS emission...
Table 4.1: Summary of sources observed at Mopra, along with those detected in CS at 3σ or greater and 5σ or greater (where σ is the rms noise on the spectra), including sources that were detected in Class I CH$_3$OH maser emission at 5σ or greater.

<table>
<thead>
<tr>
<th>Source Description</th>
<th>CS J=1-0 Total observed</th>
<th>3σ limit</th>
<th>5σ limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total observed</td>
<td>270</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detected in Class I CH$_3$OH at 5σ limit</td>
<td>194</td>
<td>179/247</td>
<td>144/216</td>
</tr>
<tr>
<td>Not detected in Class I CH$_3$OH at 5σ</td>
<td>76</td>
<td>68/247</td>
<td>72/216</td>
</tr>
</tbody>
</table>

Table 4.2: Summary of sources observed in NH$_3$ at Parkes including those detected in NH$_3$ (1,1), (2,2) and (3,3) at 5 times the rms noise in the spectra.

<table>
<thead>
<tr>
<th>Source Description</th>
<th>NH$_3$ Total observed</th>
<th>5σ limit</th>
<th>5σ limit</th>
<th>5σ limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Observed</td>
<td>215</td>
<td>131</td>
<td>87</td>
<td>59</td>
</tr>
</tbody>
</table>

detected at 5σ or greater. In total 215 sources were observed at Parkes in NH$_3$, of these 131 were detected at 5σ or greater in the NH$_3$ (1,1) transition, with 87 detected in NH$_3$ (2,2) and 59 detected in NH$_3$ (3,3) at 5σ or greater. As a comparison to the work in this thesis, a summary of previous NH$_3$ and CS observations is provided in Table 4.4 which is an adapted version of Table 6 given in Longmore et al. (2007a).

Table 4.3: Comparison of the sources observed at both Mopra and Parkes to 5σ detection limits.

<table>
<thead>
<tr>
<th>Source Description</th>
<th>CS with NH$_3$ (1,1) 5σ limit</th>
<th>CS with NH$_3$ (1,1) and (2,2) 5σ limit</th>
<th>CS with (2,2) and (3,3) 5σ limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detected in Class I CH$_3$OH at 5σ</td>
<td>98/124</td>
<td>78/87</td>
<td>54/59</td>
</tr>
<tr>
<td>Not detected in Class I CH$_3$OH at 5σ</td>
<td>26/124</td>
<td>9/87</td>
<td>5/59</td>
</tr>
</tbody>
</table>
4.1: OVERVIEW OF DATA AND PREVIOUS SURVEYS

The parameters, for only a sample, of the sources determined from the survey observations are given in Tables 4.5, 4.6 and 4.7. Table 4.5 gives the line parameters of the CS emission observed with Mopra, the sources are named by their Galactic coordinates, the columns give the source name, the local standard of rest velocity of the CS emission \(V_{\text{LSR}}\), the uncertainty of the local standard of rest velocity \(\sigma(V_{\text{LSR}})\), the FWHM \(\Delta \nu\), the uncertainty of the FWHM \(\sigma(\Delta \nu)\), the brightness temperature \(T^*_B\), the uncertainty on this \(\sigma(T^*_B)\) and finally the rms noise on the spectra. Table 4.6 provides the parameters determined for the Class I CH\(_3\)OH maser emission observed with Mopra, the sources are again named by their Galactic coordinates, the columns represent the sources name, the peak of the emission \(T^*_{\text{peak}}\), the velocity corresponding to the peak of the emission \(V_{\text{peak}}\), the lower extent of the velocity coverage of the emission \(V_{\text{low}}\), the higher extent of the velocity coverage of the emission \(V_{\text{high}}\) and the rms noise on the spectra. It should be noted that due to the method of fitting the Class I emission errors on the velocity coverage and peak emission are not determined for the Class I emission and are therefore noticably missing from future analysis. Table 4.7 provides the parameters of the NH\(_3\) (1,1) emission determined from the CLASS fits, the columns represent, the source name (again named by their Galactic coordinates), the local standard of rest velocity \(V_{\text{LSR}}\), the uncertainty on this velocity \(\sigma(V_{\text{LSR}})\), the line width of the main component \(\Delta \nu\), the uncertainty on this \(\sigma(\Delta \nu)\), the brightness temperature of the main component \(T^*_B\), the uncertainty on this \(\sigma(T^*_B)\), the optical depth \(\tau_{m(1,1)}\), and the uncertainty on the optical depth \(\sigma(\tau_{m(1,1)})\) and the rms noise on the spectra.

4.1.1 CS sample Selection

The CS sample was initially investigated. CS is a high gas density tracer and has a strong chance of detection toward dense regions, it is therefore a useful tool in the study of massive star forming regions. The sources were observed through pointed observations centered on the Class II maser positions and the CS should be at a similar
Table 4.4: Comparison of previous observational surveys. Only the properties of the NH$_3$ and CS emission towards massive star forming regions are considered, any additional molecular lines surveyed are not included. The average line widths are given by the column; Mean $\Delta \nu$ in kms$^{-1}$, for the NH$_3$ transition this represents the average line width of the NH$_3$ (1,1) transition.

<table>
<thead>
<tr>
<th>Paper</th>
<th>Lines</th>
<th>Beam size (arcsec)</th>
<th>Mean $\Delta \nu$ (kms$^{-1}$)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Churchwell et al. (1990)</td>
<td>NH$_3$</td>
<td>40</td>
<td>3.1</td>
<td>UCHII regions</td>
</tr>
<tr>
<td>Bronfman et al. (1996)</td>
<td>CS J=2-1</td>
<td>50</td>
<td>1.0-15.8</td>
<td>Characteristic UCHII regions</td>
</tr>
<tr>
<td>Anglada et al. (1996)</td>
<td>CS J=1-0/NH$_3$</td>
<td>41/84</td>
<td>3.7/3.1</td>
<td>H$_2$O masers in star forming regions</td>
</tr>
<tr>
<td>Zinchenko et al. (1998)</td>
<td>CS J=2-1</td>
<td>40</td>
<td>1.5-9</td>
<td>H$_2$O masers in massive star forming regions</td>
</tr>
<tr>
<td>Sridharan et al. (2002)</td>
<td>NH$_3$</td>
<td>40</td>
<td>2.1</td>
<td>Toward high mass protostellar objects</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>with no associated UCHII</td>
</tr>
<tr>
<td>Sridharan et al. (2005)</td>
<td>NH$_3$</td>
<td></td>
<td>1.6</td>
<td>Toward high mass starless cores</td>
</tr>
<tr>
<td>Pillai et al. (2006)</td>
<td>NH$_3$</td>
<td>40</td>
<td>1.7</td>
<td>Toward IRDCs</td>
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<tr>
<td>Longmore et al. (2007a)</td>
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<td>Toward hot molecular cores traced</td>
</tr>
<tr>
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<td></td>
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<td>traced by 6.7 GHz Class II</td>
</tr>
<tr>
<td>Wu et al. (2010)</td>
<td>NH$_3$</td>
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<td>1.75/3.9</td>
<td>Toward low and high luminosity</td>
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<td></td>
<td></td>
<td>6.7 GHz Class II masers respectively</td>
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<td>Hill et al. (2010)</td>
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<td>58</td>
<td>2.9</td>
<td>Toward massive star forming regions using Parkes</td>
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<tr>
<td>Fuller et al. (2011)</td>
<td>CS J=1-0</td>
<td>~60</td>
<td>4</td>
<td>Toward regions traced by Class I methanol masers</td>
</tr>
<tr>
<td>This work</td>
<td>CS/NH$_3$</td>
<td>~60/58</td>
<td>4.3/2.7</td>
<td>Toward massive star forming regions</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>traced by Class II methanol masers</td>
</tr>
</tbody>
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Table 4.5: The Gaussian fit parameters of the CS J=1-0 emission for a selection of the sources observed at Mopra. The sources are named by their Galactic coordinates, the columns give the source name, the local standard of rest velocity of the CS ($V_{\text{LSR}}$), the uncertainty of the local standard of rest velocity ($\sigma(V_{\text{LSR}})$), the FWHM ($\Delta\nu$), the uncertainty of the FWHM ($\sigma(\Delta\nu)$), the brightness temperature ($T_B^*$), the uncertainty on this ($\sigma(T_B^*)$) and finally the rms noise on the spectra.

<table>
<thead>
<tr>
<th>Source</th>
<th>$V_{\text{LSR}}$</th>
<th>$\sigma(V_{\text{LSR}})$</th>
<th>$\Delta\nu$</th>
<th>$\sigma(\Delta\nu)$</th>
<th>$T_B^*$</th>
<th>$\sigma(T_B^*)$</th>
<th>rms</th>
</tr>
</thead>
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<td>G002.1434+00.0091</td>
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<td>0.09</td>
<td>0.57</td>
<td>0.01</td>
<td>0.03</td>
</tr>
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<td>6.49</td>
<td>0.17</td>
<td>0.52</td>
<td>0.01</td>
<td>0.04</td>
</tr>
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<td>0.60</td>
<td>0.01</td>
<td>0.04</td>
</tr>
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<td>4.81</td>
<td>0.08</td>
<td>0.91</td>
<td>0.01</td>
<td>0.04</td>
</tr>
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<td>0.29</td>
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<td>0.04</td>
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<td>3.77</td>
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<td>0.63</td>
<td>0.01</td>
<td>0.04</td>
</tr>
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<td>0.03</td>
<td>6.19</td>
<td>0.07</td>
<td>1.76</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>G009.6186+00.1932</td>
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<td>0.08</td>
<td>1.71</td>
<td>0.02</td>
<td>0.05</td>
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<tr>
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<td>0.04</td>
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<td>0.33</td>
<td>0.01</td>
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<td>0.37</td>
<td>0.01</td>
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<tr>
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<td>0.13</td>
<td>0.45</td>
<td>0.01</td>
<td>0.03</td>
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</table>
Table 4.6: The parameters determined for the 44 GHz Class I CH$_3$OH maser emission for a selection of the sources observed at Mopra. The sources are named by their Galactic coordinates, the columns represent the sources name, the peak of the emission ($T_{\text{peak}}^*$), the velocity corresponding to the peak of the emission ($V_{\text{peak}}$), the lower extent of the velocity coverage of the emission ($V_{\text{low}}$), the higher extent of the velocity coverage of the emission ($V_{\text{high}}$), and the rms noise on the spectra.

<table>
<thead>
<tr>
<th>Source</th>
<th>$T_{\text{peak}}^*$ (K)</th>
<th>$V_{\text{peak}}$ (km/s)</th>
<th>$V_{\text{low}}$ (km/s)</th>
<th>$V_{\text{high}}$ (km/s)</th>
<th>rms (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G003.4421-00.3484</td>
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<td>-25.29</td>
<td>-29.38</td>
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<tr>
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<td>-27.23</td>
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<tr>
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<td>-37.17</td>
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<td>105.82</td>
<td>117.52</td>
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</table>
Table 4.7: The CLASS fit parameters for the NH$_3$ (1,1) observations for a selection of the sources observed at Parkes, the columns represent, the source name (again named by their Galactic coordinates), the local standard of rest velocity ($V_{\text{LSR}}$), the uncertainty on this velocity ($\sigma (V_{\text{LSR}})$), the line width of the main component ($\Delta \nu$), the uncertainty on this ($\sigma (\Delta \nu)$), the brightness temperature of the main component ($T_B^*$), the uncertainty on this ($\sigma (T_B^*)$), the optical depth ($\tau_{m(1,1)}$), and the uncertainty on the optical depth ($\sigma (\tau_{m(1,1)}$)) and the rms noise on the spectra.

<table>
<thead>
<tr>
<th>Source</th>
<th>$V_{\text{LSR}}$</th>
<th>$\sigma (V_{\text{LSR}})$</th>
<th>$\Delta \nu$</th>
<th>$\sigma (\Delta \nu)$</th>
<th>$T_B^*$</th>
<th>$\sigma (T_B^*)$</th>
<th>$\tau_{m(1,1)}$</th>
<th>$\sigma (\tau_{m(1,1)}$)</th>
<th>rms</th>
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<td>0.05</td>
<td>1.96</td>
<td>0.12</td>
<td>0.02</td>
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<td>1.83</td>
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<td>0.03</td>
<td>0.81</td>
<td>0.09</td>
<td>2.71</td>
<td>0.17</td>
<td>0.03</td>
</tr>
<tr>
<td>G009.6210+00.1957</td>
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<td>0.04</td>
<td>3.76</td>
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<td>0.47</td>
<td>0.04</td>
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<td>0.03</td>
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V_{LSR} to the maser emission. The CS V_{LSR} are then compared to the ATCA Class II V_{LSR}. Figure 4.1 shows the histogram of the difference in velocity between the peak of the Class II maser emission and the CS (V_{ATCA} - V_{CS}). The upper panel of Figure 4.1 shows all 270 sources which were observed in CS, ~ 20% of the 270 sources have a difference between their respective CS and ATCA velocities of > |10| \text{ kms}^{-1}. The spectra of these sources were then analysed to try and determine the reason for the large velocity difference, up to ~ ± 150 \text{ kms}^{-1} in some sources. On investigation it appears that there are two main reasons for the inconsistencies between the velocities; the CS line is either too weak to be detected and some part of the noise has subsequently been fitted or the Gaussian has been fitted to the wrong component in the spectra. As discussed previously (Section 3.4.2) when reducing the CS data the ATCA V_{LSR} was
unknown and typically the strongest component in the CS spectra was found by the fit. It appears, however, for a small sample of the sources (13 out of 270) the secondary CS component (the ncomp=2) have a velocity which is more closely associated with the Class II emission. For any of the CS sources which have an ncomp=1 velocity component $> |10| \text{kms}^{-1}$ from the peak of the Class II methanol maser emission and an ncomp=2 or ncomp=3 component which is $< |10| \text{kms}^{-1}$ again from the peak of the methanol emission, the velocity was changed to the respective ncomp=2 or ncomp=3. This velocity component was then amended to the one with the closest association to the CH$_3$OH maser emission and used in the rest of the analysis. With the aim of providing a sample that gives a high confidence level, representative of true detections, 3$\sigma$ and 5$\sigma$ detections limits were placed on the sample (the noise used to determine the limits is given by the rms of the baseline of the CS spectra) and are displayed in lower panels of Figure 4.1. This reduces the sample size to 247 and 216 for 3$\sigma$ and 5$\sigma$ detections respectively (Table 4.1). It is clear from Figure 4.1 that using a 5$\sigma$ detection level removes sources that have the largest difference between their CS and ATCA $V_{\text{LSR}}$, providing a sample with a maximum velocity difference of $\sim < |20| \text{kms}^{-1}$. To try and determine which detection limit best represents the complete sample, sources with detection limits in the range $> 3\sigma$ and $< 5\sigma$ were manually inspected. Within this range, there are indeed sources which show ambiguity and it is unclear if they represent a true detection or not. In contrast some of these spectra show clear emission with a velocity corresponding to the Class II maser emission. Taking the 5$\sigma$ level will then remove sources that do evidently show emission. In the context of obtaining a sample representing the highest confidence level of sources with true detections, the 5$\sigma$ detection limit will be used, unless stated otherwise in the future analysis. This will reduce the noise in the sample at the cost of also removing some actual true detections.
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Figure 4.2: Distribution of the difference between the ATCA $V_{\text{LSR}}$ and the NH$_3$ (1,1) $V_{\text{LSR}}$ for sources where the NH$_3$ (1,1) emission has been detected at the greater than 5$\sigma$ limit.

4.1.2 Ammonia Sample Selection

Using Parkes, 215 sources were observed simultaneously in the NH$_3$ (1,1), (2,2) and (3,3) transitions. Placing 5$\sigma$ detection limits (as with the CS) on the NH$_3$ emission, reduces the sample to 131 detections for sources with NH$_3$ (1,1) emission (see Table 4.2). Selecting sources with NH$_3$ (1,1) and associated CS emission at 5$\sigma$ reduces the sample to 124 (Table 4.3). As all Parkes sources have Mopra counterparts the reduction from 131 with only ammonia to 124 when associating CS is surprising. On inspection the 7 sources with (1,1) detections $> 5\sigma$ and CS detections $< 5\sigma$ were found to have a high rms noise values of approximately twice the typical baseline rms. This increase in noise reduces the signal to noise level, rendering them non detections in CS at 5$\sigma$. The association of the NH$_3$ (1,1) $V_{\text{LSR}}$ to the Class II methanol ATCA $V_{\text{LSR}}$ is displayed in
4.2: INVESTIGATING THE MOPRA DATA

Figure 4.2. The difference between the ATCA $V_{\mathrm{LSR}}$ and the NH$_3$ (1,1) $V_{\mathrm{LSR}}$ is found to be $\leq |23|$ km s$^{-1}$ which is comparable to the difference found between the ATCA $V_{\mathrm{LSR}}$ and the $V_{\mathrm{LSR}}$ of the CS emission (Figure 4.1). The mean and standard deviation are $-0.02$ km s$^{-1}$ and $4.9$ km s$^{-1}$ respectively for the distribution of the ATCA to NH$_3$ (1,1) $V_{\mathrm{LSR}}$ shown in Figure 4.2. In comparison the mean and standard deviation of the velocity distribution of the ATCA and CS $V_{\mathrm{LSR}}$ is found to be $0.05$ km s$^{-1}$ and $5.7$ km s$^{-1}$ at a detection of $3\sigma$ or greater, with a mean and standard deviation of $0.3$ km s$^{-1}$ and $4.3$ km s$^{-1}$ for sources with a CS detection at $5\sigma$ or greater (Figure 4.1).

4.2 Investigating the Mopra Data

4.2.1 Investigation of CS line widths

It is possible to investigate the dynamics and kinematic structure of massive star forming regions through the bulk motion and internal motions of the gas, which can be investigated through the line widths of varying chemical species. The thermal properties of the gas resulting in Doppler broadening, turbulence within the region as well as bulk velocity structure along the line of sight can have an effect on the observed spectral line structure.

A histogram showing the FWHM of the CS sources is shown in the upper panel of Figure 4.3. The line widths are found to have a mean, median and standard deviation of $4.5$ km s$^{-1}$, $4.1$ km s$^{-1}$ and $1.95$ km s$^{-1}$ respectively. The line widths vary from $1.43$ km s$^{-1}$ to $16.3$ km s$^{-1}$, displaying a tail towards line widths broader than $\sim 8$ km s$^{-1}$. This is higher than the average CS $J=1$-0 line widths of $3.7$ km s$^{-1}$ and range of $2$–$5$ km s$^{-1}$ found by Anglada et al. (1996). Anglada et al. (1996) observe the CS at higher resolution $\sim 41''$, which could be resolving out some of the extended CS structure, the variation in source distances surveyed in Anglada et al. (1996) varies from $\sim 0.4$–$15$ kpc, with about a third of the sources being at a distance $\geq 5$ kpc, which at the resolution observed would resolve typically a 1 pc region in the CS, corresponding to the typi-
Figure 4.3: Histogram of the CS FWHM. The upper panel consists of all sources prior to spectra with emission displaying possible blended structure being re-fitted. The lower panel is the sample with updated fit parameters for sources successfully re-fitted with two Gaussians.

...cal extension of the CS emission (Anglada et al. 1996). The distances to sources are not known for this data, the resolution obtained at Mopra for the CS emission would resolve the whole extension of the CS emission at $\sim 3$ kpc. The difference in the resolution will account for some deviation in the line width values for sources at closer distances, but are too great for resolution to be the sole factor. The differences could also be associated to the variance in the groups of objects observed, Anglada et al. (1996) sample star forming regions traced by H$_2$O maser emission which could potentially trace both low, intermediate and high mass star formation, as opposed to only massive star forming regions in this analysis. This could possibly account for the variance as the smaller, less turbulent low mass star forming regions would add lower line width values into their sample. When comparing the line width results to a survey only
4.2: INVESTIGATING THE MOPRA DATA

sampling massive star forming regions (Zinchenko et al. 1998), the extension toward values of 16.3 kms$^{-1}$ in the CS line widths is still not found. Zinchenko et al. (1998) find the CS J=2-1 line widths to extend over a range $\sim 1.5 - 9$ kms$^{-1}$ which underestimates the range seen in Figure 4.3. The observations by Bronfman et al. (1996) in the CS J=2-1 transition do extend up to comparable line widths of 15.8 kms$^{-1}$, however, they state there is some non negligible deviation in the shape of the emission structure and an uncertainty in the Gaussian fits.

**Blended Emission**

Considering the broader line widths found towards the tail of Figure 4.3 and the higher limit of CS line widths in the Zinchenko et al. (1998) sample, along with the uncertainty in sources with the largest line widths found by Bronfman et al. (1996), the spectra of sources with line widths $>8$ kms$^{-1}$ were subsequently inspected. The spectra of 10 sources display a possible blended structure in their emission with two closely associated peaks causing an extension in their single Gaussian fitted line width estimates. As the CS emission was fitted using only a single Gaussian, emission lines that have closely blended emission are unable to be resolved. Sources with a visually discernable blended feature were fitted with a double Gaussian; the fit parameters of the component showing closest association in velocity to the Class II emission were subsequently used for the remainder of the analysis. The new histogram of the CS line widths with the updated blended emission fits can be seen in the lower panel of Figure 4.3. The range over which the line widths extend is then reduced from 16.3 kms$^{-1}$ to 10.2 kms$^{-1}$ with a new mean and median of 4.3 kms$^{-1}$ and 4.0 kms$^{-1}$ respectively. This new upper limit on the range is then comparable to the results found by Zinchenko et al. (1998). The blended nature of some of the emission profiles may also explain the high upper limit in the Bronfman et al. (1996) survey. The line widths of the new sample taking into account the blended emission are still, however larger than Anglada et al. (1996) and Zinchenko et al. (1998). The remaining sources in the corrected sample with broad line widths may also contain blended emission; however, their spectra
show no discernable features in their emission that allows a firm determination to be made. Further observations would be required to understand the structure of the emission. For spectra that are successfully fitted with a double Gaussian the parameters of the new fit that have the closest association to the ATCA velocity will be used for the remainder of this work. The unclear lines, however, remain in the sample.

4.2.2 CS With and Without Associated Class I Methanol Maser Emission

A major goal of this research is to try and ascertain if the environments of sources with Class I masers differ to those without and understand if they represent an evolutionary scheme. The sources were then split into two; sources having associated CS and Class I CH$_3$OH maser detections and those without. At the 5σ detection limit 216 sources are found to have CS detections, of these 144, which corresponds to approximately 66% of the sources have a 44 GHz Class I detection (also at the 5σ limit). This is a vastly larger detection rate in comparison to the recent paper by Fuller et al. (2011) that find a detection rate of 26% from their unbiased sample of 32 Class I 44 GHz maser sources. While it is also lower than the detection rate of 72% expressed by Val’tts & Larionov (2007) and 89% found by Cyganowski et al. (2009). The higher detection rate in the (Cyganowski et al. 2009) survey could be to due to their higher sensitivity observations. At the 6σ limit they reach levels of 0.15 Jy, in comparison, the sensitivity limit of this survey is on average reaching an rms for the 44 GHz spectra of 0.032 K at 1σ or 2.14 Jy flux limit at 5σ. When using the Cyganowski et al. (2009) detection limit, the detection rate for this sample changes to 69% which is still significantly lower. Cyganowski et al. (2009) specifically target EGOs, this would also add bias and possibly account for their higher Class I detection rate, given the close expected association of Class I masers to outflow regions. The higher detection rate found by Val’tts & Larionov (2007), can possibly be attributed to the larger extent over which they associate detections. Classifying a detection up to a maximum separation of 120″, Class I
emission from closely associated massive star forming regions is likely included when
sampling more distant sources, therefore overestimating the true amount of detections.

Fuller et al. (2011) use the Mopra telescope in the same configuration as used in
this data, this removes the ambiguity over the resolution as a factor in the detection rate
variance. The significantly lower detection rate found by Fuller et al. (2011) is possibly
due to a number of systematic and semantic based properties. Within their survey an
association is classed as being within 30′′ which is exactly half of the beam size that
is used in this analysis, when considering the detection rate in one full beam size a
detection rate of approximately 35 % is given. The higher detection rate produced
when extending the beam size is still nearly half as low the 66 % found in this sample.
The average 5σ flux limit used in (Fuller et al. 2011) is 8 Jy this is nearly 4 times greater
than the 5σ sensitivity limit of 2.14 Jy obtained for the Class I detections in this work.
The large difference in 5σ flux levels is due to the observing procedure, more time was
spent on individual sources in the pointed observations used in this work, than in the
mapping technique used in the Fuller et al. (2011) survey. When using the flux limit
of 8 Jy on our data, a new detection rate of 39 % is found, this is comparable to the
Fuller et al. (2011) detection rate. This would indicate that the variance in detection
rates when using similar beam sizes is a signal to noise effect and not intrinsic to the
Class I emission. The velocity structure of the Class I emission is discussed in Section
4.2.3, additionally the properties of the Class I emission in comparison to the Class
II maser emission are explored further. Section 4.2.5 looks at the velocity difference
between the Class I and peak of the Class II emission, with Section 4.2.7 investigating
the variation in the flux between the Class I and Class II masers.

CS Line Widths
The FWHM of the respective sample groups can be seen in Figure 4.4, which displays
histograms of the line widths of the CS lines with (upper panel) and without (lower
panel) Class I CH$_3$OH maser detections. The line widths range from 1.43–8.53 kms$^{-1}$
and 2.08–10.15 kms$^{-1}$ for sources with no 44 GHz Class I detected emission and those
with a 44 GHz Class I maser detection. The sources without Class I detections have a mean and median of 4.02 km/s and 3.78 km/s respectively, while sources with Class I detections appear to have broader line widths having mean and median values of 4.65 km/s and 4.27 km/s. The values of the detected sample while comparable are higher than the range of 2–9 km/s and median of 4.0 km/s found by Fuller et al. (2011). This could be due to the sources with un-resolvable blended emission still contaminating the sample. The broadening of the CS line widths between sources with and without detected Class I maser emission, could be due to increased turbulence in the Class I detected sample. The expected association of the outflow in the Class I detected sources could be causing the increase in the broadening seen in the CS line widths, if they are tracing the outflow region. Without higher resolution it is difficult
to constrain where the emission is originating from within the beam. To determine if there is any statistical significance between the broadening in the line widths between the two sample groups a KS test was performed. A KS test compares two data sets of varying length, the hypothesis is set that that the two samples are representing the same population of objects. Comparing the distributions between the two samples the KS test will either accept or reject the null hypothesis along with providing the confidence level of the outcome. Essentially it can be used to test the likelihood that two different sets of data are representing the same population of objects. For the CS line widths the KS test shows that there is no evidence that the sources with and without Class I masers are drawn from the different populations, having a confidence level of only 0.53.

**CS and ATCA Flux**

Comparison of the flux of the CS emission for the detected and non detected sources is displayed in Figure 4.5. The detected sample, have on average higher CS flux values, the sources with Class I detections have a mean and median CS flux of 11.8 Jy and 9.8 Jy in comparison to the lower values of 7.2 Jy and 6.5 Jy for sources with no Class I maser detected emission. Maximum CS flux values of the Class I detected sources are also nearly twice as high as the non detected sample. Without knowing distances to sources along with the inability to resolve the core size and structure of the CS within the region it is difficult to make firm comparisons between the two samples. It must also be stressed that the CS intensities have not been calibrated for atmospheric effects due to elevation, so can only be used a guide to the broad picture with no firm conclusions possible yet. For the CS intensities a KS shows no evidence that sources with detected Class I maser emission are from a different population to sources with no associated Class I maser emission. Figure 4.6 also shows an increase in the ATCA determined Class II maser flux for sources with Class I detections compared to sources without Class I masers. The detected sample has an extremely large spread in the ATCA flux values with maximum detected flux levels of 5000 Jy considerably larger
than the 780 Jy achieved in sources with no associated Class I maser emission. The distribution of the mean flux values between the two source groups is then vastly different. Considering the median flux values of the distribution the sources with Class I maser emission display a median flux of 9.00 Jy in comparison to 4.75 Jy for the non-detected sample. Again a KS test provides no evidence that the ATCA flux found for sources with Class I emission are from a different population of objects as those sources without Class I detected masers.

### 4.2.3 44 GHz Class I Methanol Line Widths

Investigation of the Class I emission properties, could allow insight into the dynamics of their environments. The Class I line widths are displayed in Figure 4.7. The line
Figure 4.6: Histograms of the logarithm of the ATCA flux (Jy) for sources with a Class I CH$_3$OH maser detection in the upper panel and sources without a corresponding Class I CH$_3$OH maser detection are shown in the lower panel.

widths are clearly broader than the CS line widths, having a mean and median of 8.9 kms$^{-1}$ and 8.2 kms$^{-1}$ over the range 2.4–27.9 kms$^{-1}$. The 44 GHz line widths, however, should typically be broader than the CS. As detailed previously (Section 3.4.3) the line widths of the Class I CH$_3$OH maser emission were not fitted with a Gaussian, the line widths displayed in Figure 4.7 represent the total velocity coverage of the Class I emission structure. The CS line widths are represented by the FWHM of the single Gaussian fit which represents the width at half the peak intensity of the emission and as such typically underestimates the total CS velocity coverage, missing the Gaussian wings. The CS emission could then be associated with the broader Class I maser emission if the ratio of the Class I velocity coverage to the CS FWHM is within a ratio of about 2. The ratio of the line widths of the Class I emission to that of the CS
emission is displayed in Figure 4.8 and $\sim 65\%$ of the sources have a ratio less than 2 therefore possibly attributed to the same gas structure within the region. Fuller et al. (2011) find that the Class I to CS ratio for all their sources fall within the range 0.7 -2.3, which represents $\sim 70\%$ of the sources in this data.

### 4.2.4 Class I Dynamical Structure

The structure of maser emission is typically quite complex, along with a higher intensity peak spike there is also an lower intensity emission within a given velocity range. Comparison of the peak velocity ($v_{peak}$) to that of the mid-point of the velocity ($v_{mean}$) over the total emission range could potentially provide some interesting information on the structure of the emission. The difference in the mean velocity to that of the peak
Figure 4.8: Histogram of the ratio of the 44 GHz Class I CH$_3$OH velocity coverage to the CS FWHM.

is plotted in Figure 4.9 for the sources detected with Class I maser emission. The mean and median of this velocity difference is $0.096 \text{ km s}^{-1}$ and $0.074 \text{ km s}^{-1}$ respectively. The distribution shown in Figure 4.9 looks similar to the distribution shown by Fuller et al. (2011) for the difference in the mean of the 44 GHz Class I maser to that of the peak emission. The nature of this offset is however unclear. It may suggest that the peak of the emission is slightly blueshifted respective to its mean emission over the range, therefore on average the peak emission is redshifted relative to the mean point of the emission.

### 4.2.5 Class I Association to Class II

The distribution of the difference in the velocity of the peak of the Class II maser emission to that of the peak and mean of the Class I maser emission is displayed in
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Figure 4.9: A histogram of the distribution of the difference between the mean of the velocity range of the Class I CH$_3$OH maser emission $v_{\text{mean}}$ and the peak $v_{\text{peak}}$ of the Class I CH$_3$OH maser emission.

Figure 4.10. Both the peak and mean of the Class I CH$_3$OH emission show average negative offsets of $-0.35$ kms$^{-1}$ and $-0.44$ kms$^{-1}$ respectively, compared to the $V_{\text{LSR}}$ of the Class II emission. Suggesting that on average the Class I emission is more redshifted than the Class II emission relative to our reference frame.

4.2.6 Class I Association to CS

The CS peak emission has a positive velocity offset of approximately 0.5 kms$^{-1}$ to 0.6 kms$^{-1}$ to the peak and mean of the Class I maser emission which can be seen in Figure 4.11. This is similar to offsets detected by Fuller et al. (2011) of 1 kms$^{-1}$. The CS to Class I velocity offsets have a smaller range $-2.9$ kms$^{-1}$ to 3.8 kms$^{-1}$ in comparison to the CS to Class II velocities shown in Figure 4.1 which have a velocity offset range of
4.2: INVESTIGATING THE MOPRA DATA

Figure 4.10: A histogram of the distribution of the difference between ATCA 6.7 GHz Class II CH$_3$OH maser $V_{\text{LSR}}$ to the 44 GHz Class I CH$_3$OH maser $V_{\text{LSR}}$.

$\sim < |20| \text{km}s^{-1}$.

4.2.7 Class I and ATCA Flux

It has been previously suggested that there is an evolutionary sequence for objects containing different classes of methanol maser emission (Ellingsen 2006). Class I masers are typically believed to occur at an earlier, cooler stage, whereas Class II masers are radiatively pumped and thought to occur at a some later evolutionary stage (Cragg et al. 1992). Figure 4.12 displays the logarithm of the peak of the Class I to the peak of the Class II flux ratio against the CS line widths, there appears to be no correlation between increasing flux ratios (Class I emission $>$ Class II emission) and CS line widths values. A similar number of sources are found to have a Class I flux $>$
Class II flux as sources with Class I emission < Class II emission. Interestingly some sources display Class I fluxes that are 20 times higher than their Class II counterparts. One source displays a Class I flux that is >80 times the Class II emission. Comparing sources where the Class I emission is greater than the Class II emission to those sources where the Class I emission is less than Class II emission, both show a similar range in CS line widths, having a comparable mean of 4.5 km s$^{-1}$ and 4.8 km s$^{-1}$ for a ratio > 1 and a ratio < 1 respectively. Performing a KS test on the two groups suggests that the two groups are from the same population of objects at a confidence of 0.9. Previous work by Pratap et al. (2008) (Section 2.2.1) suggest a flux ratio of 5 between different Class I maser transitions can provide evidence of different evolutionary stages. When splitting the sample at a ratio of 5, only 17 % of the sources are found to have Class I fluxes greater than 5 times their respective Class II fluxes. The CS line widths for
sources with Class I to Class II flux ratios greater than 5 and less than 5 are shown in the upper and lower panel of Figure 4.13 respectively. The sources where the Class I emission is more than 5 times greater than the Class II emission extend over a smaller range and miss the broader tail shown in sources where the Class I emission is less than 5 times the Class II emission. For sources with a ratio greater than 5 the mean is 4.36 kms$^{-1}$ as opposed to 4.7 kms$^{-1}$ for sources with a ratio less than 5. In contrast to the result of the KS test when splitting the sample at a Class I to Class II flux ratio of 1, the KS test when dividing the sample at a flux ratio of 5 suggests that the two populations are not from the same sample of objects, however, with a confidence of $\sim 0.8$. Further investigation would be required to place any firm conclusions on the differences, if any, between sources with Class I flux greater than Class II emission to
some level.

The Class I maser emission is known to be tracing the outflow region, it is therefore interesting to see if there is any correlation between the flux of the Class I to Class II emission and the velocity coverage of the Class I emission. This relation is plotted in Figure 4.14, the Class I line widths appear to have a possible correlation, with slightly increasing line widths toward decreasing peak Class I to Class II flux ratios. Wu et al. (2010) found through observations of the outflow tracer $^{12}$CO that sources containing high luminosity Class II masers were found to have broader $^{12}$CO line widths. This is consistent with the correlation seen in Figure 4.14 as lower Class I to Class II flux ratio values imply an increase in Class II flux. The nature of maser emission, however makes it difficult to attribute exactly what the Class I line width broadening infers about structure of the outflow region. The variability of the Class II maser emission and the possible variation in the Class I maser emission must be taken into account when considering any correlations in Figures 4.12, 4.13 and 4.14.

### 4.3 Investigation of Parkes Data

As detailed previously the metastable ammonia transitions are an extremely useful environmental probe, allowing investigations into not only the temperature, but also the density. The inversion transitions trace increasingly warmer environments allowing an insight into the different layers of the massive star forming region. From the 215 sources originally observed with Parkes simultaneously in the NH$_3$ (1,1), (2,2) and (3,3) there were 131 sources detected with NH$_3$ (1,1) emission at the 5$\sigma$ limit. This reduces to 87 for those sources with NH$_3$ (1,1) and (2,2) emission and 59 for sources detected with NH$_3$ (1,1), (2,2) and (3,3) at 5$\sigma$ detection limits (see Table 4.2).
4.3: INVESTIGATION OF PARKES DATA

Figure 4.13: Histogram of the CS FWHM, upper panel displays sources that have a Class I to Class II flux ratio > 5, the lower panel represents the CS FWHM for sources with a Class I to Class II flux ratio < 5.

4.3.1 NH$_3$ (1,1) Line Widths

The line widths can provide an insight into the internal motions and kinetic energy of the region. A histogram displaying the line widths for the NH$_3$ (1,1) transition toward the Class II methanol masers is displayed in Figure 4.15. The line widths vary from 1.2 kms$^{-1}$ to 5.5 kms$^{-1}$ with a mean and median of 2.7 kms$^{-1}$ to 2.5 kms$^{-1}$ respectively. The standard deviation on the mean is 0.9 kms$^{-1}$. The line widths are approximately 1 kms$^{-1}$ broader than found by Pillai et al. (2006) and Sridharan et al. (2005), however, their target regions are IRDCs and high mass starless cores respectively. Ammonia emission tracing IRDCs and starless cores will almost certainly be on average colder and less turbulent than the typically more evolved regions inhabited by hot molecular cores and Class II methanol masers. In contrast Churchwell et al. (1990) found broader
average NH$_3$ (1,1) line widths of 3.1 kms$^{-1}$, with only 70% of their sample display NH$_3$ (1,1) line widths ≤ 4 kms$^{-1}$ compared to 88% in this data. The broader NH$_3$ (1,1) line widths found by Churchwell et al. (1990) could be attributed to the typically more evolved warmer UCHII regions they target, indicating possibly that these regions are also more turbulent than molecular cores harbouring Class II methanol masers. When targeting only high mass protostellar objects with no associated UCHII regions, Sridharan et al. (2002) still find lower average line width values of 2.0 kms$^{-1}$ for their sample of 69 objects. A similar result to Sridharan et al. (2002) is found by Longmore et al. (2007a), finding from their survey of hot molecular cores, average NH$_3$ (1,1) line widths of 1.85 kms$^{-1}$ which is considerably lower than those found here. Interestingly when Longmore et al. (2007b) split the sample from Longmore et al. (2007a) up into groups, a value of 2.43 kms$^{-1}$ is found for NH$_3$ (1,1) line widths in the cores where
only ammonia and Class II methanol maser emission is present. They found a broader average NH$_3$ (1,1) line width of 3 kms$^{-1}$ toward cores containing Class II and 24 GHz continuum emission. This suggests that the regions traced by Class II emission observed here may be more evolved having associated continuum emission, however, without more in depth analysis and continuum emission observations it is difficult to make strong comparisons. The higher line width values could also be a resolution effect, the higher resolution in the Longmore et al. (2007a) survey could be resolving out some of the more expected extended structure from the NH$_3$ (1,1) emission, reducing the size of the region and the line widths.
4.3.2 $\text{NH}_3$ (1,1) and (2,2) line widths

The $\text{NH}_3$ (1,1) and (2,2) transitions are believed to be tracing the more extended core, and are typically thought to be tracing the same region within the cloud. Figure 4.16 displays histograms of the 87 sources that are detected in both the $\text{NH}_3$ (1,1) and (2,2) transitions. The line widths of the $\text{NH}_3$ (2,2) emission, shown in the lower panel of Figure 4.16, are on average broader with a mean of 3.1 $\text{km s}^{-1}$ and standard deviation of 0.9 $\text{km s}^{-1}$ as opposed to 2.8 $\text{km s}^{-1}$ and 0.9 $\text{km s}^{-1}$ for the $\text{NH}_3$ (1,1) transitions. The range of the line widths for the $\text{NH}_3$ (1,1) emission does extend up to higher values than the $\text{NH}_3$ (2,2) emission but only by $\sim 0.3$ $\text{km s}^{-1}$. The $\text{NH}_3$ (1,1) line widths in the upper panel of Figure 4.16 are also broader than those in Figure 4.15, where the whole $\text{NH}_3$ (1,1) sample is displayed. This relation between the $\text{NH}_3$ (1,1) and broader $\text{NH}_3$ (2,2) line widths has previously been observed by Pillai et al. (2006) towards IRDCs and Hill et al. (2010) when observing massive star forming regions. Both surveys find $\text{NH}_3$ (2,2) emission displaying slightly increased line widths in comparison to the line widths of the $\text{NH}_3$ (1,1) emission. Pillai et al. (2006) suggest that in some sources where the $\text{NH}_3$ (2,2) line widths are broader than the $\text{NH}_3$ (1,1), the $\text{NH}_3$ (1,1) and (2,2) emission may not be exactly tracing the same gas in the region. This could be indicating that the regions with $\text{NH}_3$ (2,2) emission are tracing different possibly more turbulent or warmer regions than those without $\text{NH}_3$ (2,2) emission. The contribution from thermal broadening to the $\text{NH}_3$ line widths when the kinetic temperature of the region is $\sim 20$K is found to be $\sim 0.22$ $\text{km s}^{-1}$, $\sim 55\%$ of the sources have (2,2) emission with line widths which are 0.22 $\text{km s}^{-1} >$ than the $\text{NH}_3$ (1,1) emission. Suggesting for greater than half the sources with $\text{NH}_3$ (1,1) and (2,2) emission the broadening is not purely thermal, however this is based on the assumption that the kinetic temperature is 20 K. Wu et al. (2010) also found that the $\text{NH}_3$ (2,2) emission have broader line widths than the $\text{NH}_3$ (1,1) emission. They found a difference of 0.2 $\text{km s}^{-1}$ for both their low and high luminosity Class II CH$_3$OH maser samples between the $\text{NH}_3$ (2,2) and $\text{NH}_3$ (1,1) line widths. Contrary to the suggestion made by Pillai et al. (2006)
that the two transitions in some cases are not exactly tracing the same region, Wu et al. (2010) believe that both lines are tracing identical regions of the cores. Longmore et al. (2007a) also find a similar morphology between the NH$_3$ (1,1) and NH$_3$ (2,2) emission suggesting that in their survey the NH$_3$ (1,1) and NH$_3$ (2,2) emission are tracing the same gas within the clouds. Considering the deviation of the line widths between the NH$_3$ (1,1) and (2,2) emission for individual sources, Figure 4.17 displays a histogram of the ratio of the (2,2) to (1,1) emission. The mean and standard deviation of the ratio shown in Figure 4.17 is 1.1 and 0.2 respectively. This would suggest that on average the NH$_3$ (1,1) and (2,2) emission is likely tracing the same regions. Figure 4.17 however shows sources with a NH$_3$ (2,2) to (1,1) ratio of > 1.5 which suggests in those sources the NH$_3$ (1,1) and (2,2) emission may not be tracing the same gas.

### 4.3.3 NH$_3$ (1,1), (2,2) and (3,3) Line Widths

The NH$_3$ (1,1), (2,2) and (3,3) are at temperatures of 23, 64 and 120 K above the ground state. The NH$_3$ (1,1) and (2,2) transitions are believed to trace the more extended gas, however, the NH$_3$ (3,3) emission is believed to be emitted closer to the warmer core. Exploring the line widths of the NH$_3$ (3,3) emission is then particularly interesting in comparison to the line widths of the NH$_3$ (1,1) and (2,2) emission. The histograms of the line widths of the NH$_3$ (1,1), (2,2) and (3,3) emission for sources detected in all three transitions at 5σ detection levels are displayed in Figure 4.18. There is clearly a broadening in the line widths toward the higher energy NH$_3$ (3,3) transition, with average line width values increasing from 3.05 kms$^{-1}$, 3.3 kms$^{-1}$ and 4.57 kms$^{-1}$ for the NH$_3$ (1,1), (2,2) and (3,3) transitions respectively. The standard deviation on the distribution of the line widths is similar for the NH$_3$ (1,1) and (2,2) emission with a value of $\sim$ 0.9 kms$^{-1}$ and higher for the NH$_3$ (3,3) emission at $\sim$ 1.3 kms$^{-1}$. The line widths of the NH$_3$ (3,3) emission would be expected to be broader than the corresponding line widths of the NH$_3$ (1,1) and (2,2) emission, as the NH$_3$ (3,3) emission is tracing warmer gas, however an average increase of $\sim$ 1.27 kms$^{-1}$ between the line widths of
the NH$_3$ (2,2) to the (3,3) emission is considerably large. This trend in increasing line widths towards higher energy transitions observed by Longmore et al. (2007a) when comparing the NH$_3$ (1,1) and (2,2) emission to NH$_3$ (4,4) emission. Longmore et al. (2007a) conclude that the increased line widths in the higher energy transitions cannot be solely attributed to thermal broadening due to enhanced temperatures. Suggesting a systematic contribution from possibly rotation, infall and/or outflow or turbulence from the impact of stellar winds on the region (Longmore et al. 2007a). Without higher angular resolution it is difficult to attribute one particular systematic contribution to the increased line widths, the increase in line widths may also be influenced by several ammonia cores producing NH$_3$ (3,3) emission along the line of sight. Approximately
75\% \text{ of the sources that have detections in all three transitions have } \text{NH}_3 (2,2) \text{ line widths that are broader than the } \text{NH}_3 (1,1) \text{ line widths by } \sim 0.22 \text{ km}^{-1} \text{ which is greater than } \sim 55\% \text{ found when comparing the } \text{NH}_3 (1,1) \text{ to the } \text{NH}_3 (2,2) \text{ in Figure 4.16. The line widths of the } \text{NH}_3 (1,1) \text{ and (2,2) emission in Figure 4.16 includes both } \text{NH}_3 (3,3) \text{ emission with and without } 5\sigma \text{ detections. Removing the } \text{NH}_3 (3,3) \text{ contribution and only considering the } \text{NH}_3 (1,1) \text{ and (2,2) that don’t have } \text{NH}_3 (3,3) \text{ detections again } 55\% \text{ of the sources display this increase. Considering those sources that have } \text{NH}_3 (3,3) \text{ emission the } \text{NH}_3 (1,1) \text{ and (2,2) therefore appear less likely to be tracing the seem gas regions. Due to the association with warmer (3,3) emission, the increase in line widths due to the effect of thermal broadening will be more prevalent, and the assumption of kinetic temperatures of 20K might be underestimating the contribution of the thermal broadening, kinetic temperature estimates are then required for further}
consideration into this relationship. Considering the difference in the line widths for individual sources Figure 4.19, displays a histogram of the NH$_3$ (3,3) to (1,1) and NH$_3$ (3,3) to (2,2) line width ratios. The ratio of the (3,3) to (1,1) line widths have a mean of 1.6 with a standard deviation of 0.4 in comparison to the NH$_3$ (3,3) to (2,2) line width ratio having a mean and standard deviation of 1.4 and 0.3 respectively.

4.3.4 NH$_3$ (1,1), (2,2) and (3,3) V$_{LSR}$ Difference

Comparing the V$_{LSR}$ of the NH$_3$ (1,1) and the NH$_3$ (2,2) emission could give some indication of what level of association the regions of the gas that the corresponding transitions are tracing. Figure 4.20 displays the difference between the V$_{LSR}$ for the NH$_3$ (1,1) and (2,2) emission. The upper panel displays sources that have NH$_3$ (1,1)
Figure 4.19: Histogram of the NH$_3$ line widths ratios for sources detected in NH$_3$ (1,1), (2,2) and (3,3) emission. Upper panel shows NH$_3$ (3,3) to (1,1) ratio with the lower panel displaying the NH$_3$ (3,3) to (2,2) line width ratio.

and (2,2) emission but no NH$_3$ (3,3) emission, the lower panel of Figure 4.20 shows the $V_{\text{LSR}}$ difference for sources with NH$_3$ (1,1), (2,2) and (3,3) all at $>5\sigma$ detection limits. Both groups clearly show a positive offset with over 95% of the sources having an offset $\geq 0$. Both groups have an average offset of $\sim 0.5$ km s$^{-1}$ implying that the NH$_3$ (2,2) emission is typically blueshifted compared to the NH$_3$ (1,1) emission relative to the observers reference frame, or the NH$_3$ (1,1) emission is possibly more redshifted in respect to the NH$_3$ (2,2) emission. Understanding if there is any significance in this velocity difference between the NH$_3$ (1,1) and (2,2) emission, the $V_{\text{LSR}}$ difference between the NH$_3$ (1,1) to (3,3) and NH$_3$ (2,2) to (3,3) were subsequently plotted for those sources with NH$_3$ (3,3) emission at $5\sigma$ or greater, the results of which are shown in Figure 4.21. The NH$_3$ (1,1) to (3,3) $V_{\text{LSR}}$ difference has only a slightly positive offset,
Figure 4.20: Distribution of the difference between the $V_{\text{LSR}}$ of the NH$_3$ (1,1) and (2,2) emission. The upper panel represents sources that have no detected NH$_3$ (3,3) emission, with the lower panel displaying those sources that have NH$_3$ (3,3) emission detected.

however is approximately symmetric about zero with comparable numbers of sources having positive or negative offsets, which can be seen in the upper panel of Figure 4.21. The NH$_3$ (2,2) to (3,3) $V_{\text{LSR}}$ difference is, however, clearly negatively offset by $\sim$0.5 kms$^{-1}$. Suggesting that the NH$_3$ (3,3) is observed to be somewhat redshifted in comparison to the NH$_3$ (2,2) or the material containing the NH$_3$ (2,2) emission is blueshifted respectively to the NH$_3$ (3,3) emission.
4.3: INVESTIGATION OF PARKES DATA

Figure 4.21: Distribution of the difference between the $V_{\text{LSR}}$ of the NH$_3$ (1,1) to the (3,3) emission in the upper panel. The lower panel displays the difference between the $V_{\text{LSR}}$ of the NH$_3$ (2,2) to the (3,3) emission.

4.3.5 Temperature Determinations

Excitation Temperature

It is possible to derive the excitation temperature of the NH$_3$ (1,1) transition using the brightness temperature of the main component and the optical depth for the NH$_3$ (1,1) transition assuming a filling factor. As the hyperfine structure in the NH$_3$ (1,1) emission was sufficiently resolved, the optical depth of the NH$_3$ (1,1) transition was obtained from the fits made in CLASS. The brightness temperature of the (1,1) main component is also provided by the NH3(1,1) CLASS fitting procedure. The excitation temperature is given by the relation shown in Equation 4.1 (Pillai et al. 2006),
4: RESULTS AND ANALYSIS

\[ T_{\text{EX}} = \frac{\Delta T^*_a (1,1,m)}{1 - e^{-\tau_{m(1,1)}}} + T_{bg}, \]  

(4.1)

where \( \Delta T^*_a (1,1,m) \) and \( \tau_{m(1,1)} \) are the brightness temperature and optical depth of the NH\(_3\) (1,1) transition respectively and \( T_{bg} \) is the background temperature which has a value of 2.7K.

The excitation temperature of the NH\(_3\) (1,1) emission is found to have a mean and standard deviation on the mean of 6.05 K and 2K respectively this is in agreement with values of the NH\(_3\) (1,1) excitation temperature of 6K found by Wu et al. (2010) toward regions containing high luminosity Class II CH\(_3\)OH masers.

**Rotational Temperature**

The rotational temperatures were calculated for sources where NH\(_3\) (1,1) and (2,2) emission has been detected using Equation 4.2 (Ho & Townes 1983):

\[ T_{R12} = -41.5 \div \ln \left\{ \frac{-0.282}{\tau_{m(1,1)}} \ln \left( 1 - \frac{\Delta T^*_a (2,2,m)}{\Delta T^*_a (1,1,m)} \times (1 - e^{-\tau_{m(1,1)}}) \right) \right\}. \]  

(4.2)

Rotational temperatures for all sources containing NH\(_3\) (1,1) and (2,2) emission were derived, again assuming equal beam filling factors, both the mean and median rotational temperatures are found to be \( \approx 21K \). This value is comparable to rotational temperatures found by Churchwell et al. (1990) of 22K and higher than those found by Sridharan et al. (2002) of 19K. For sources with NH\(_3\) (1,1) and (2,2) containing no detected NH\(_3\) (3,3) emission the mean and median are both found to be \( \sim 19K \), which is lower than for sources with NH\(_3\) (3,3) emission, which were both found to have a mean and median rotational temperature of \( \sim 22K \). The rotational temperatures without NH\(_3\) (3,3) are then consistent with the values found by Sridharan et al. (2002) toward high mass protostellar candidates, whereas sources with NH\(_3\) (3,3) emission show correspondence with the values found by Churchwell et al. (1990) toward UCHII regions.
Kinetic Temperature

The kinetic temperature of the gas can be derived using the rotational temperature, determined following the procedure outlined in Tafalla et al. (2004) which is given in Equation 4.3.

\[ T_K = \frac{T_{R_{12}}}{1 - \frac{T_{R_{12}}}{42}\ln[1 + 1.1\exp\left(-\frac{16}{T_{R_{12}}}\right)]} \]  (4.3)

The average and median kinetic temperatures of the gas for sources with NH\(_3\) (1,1), (2,2) emission are found to both be \(\sim 27\)K over a range of \(\sim 18\)–\(39\) K, having standard deviation of 5K. Considering only sources with NH\(_3\) (1,1) and (2,2) emission the both the mean and median are found to be lower with values of \(\sim 23\)K. In contrast to sources that have detected (3,3) emission having higher mean and median values of \(\sim 28\)K. The standard deviation is found to be \(\sim 4\)K for sources with and without detected NH\(_3\) (3,3) emission. The kinetic temperature difference between sources with and without NH\(_3\) (3,3) emission is therefore \(\sim 5\)K, this is perhaps not completely surprising as the NH\(_3\) (3,3) emission is expected to trace warmer gas components than the NH\(_3\) (1,1) or the (2,2) which trace the colder envelope. Wu et al. (2010) find from their survey kinetic temperatures of \(\sim 28\)K and \(\sim 38\)K for sources containing low and high luminosity Class II methanol masers respectively. The values for sources specifically containing low luminosity masers is comparable to the value of \(\sim 28\)K found for sources with detected (3,3) emission. Churchwell et al. (1990), however, finds kinetic temperatures of 22K in their survey of UCHII regions which is in close agreement with the kinetic temperature found for sources with only NH\(_3\) (1,1) and (2,2) emission. For gas temperatures <30K using the properties of the (1,1) and (2,2) transitions to estimate the kinetic temperature of the gas is believed to provide a reliable estimate (Danby et al. 1988). Tafalla et al. (2004), however believe for gas temperatures >20K the kinetic temperature derived using equation 4.3 will become unreliable. For sources with only NH\(_3\) (1,1), (2,2) and no NH\(_3\) (3,3) detections only 4 % have kinetic temperature determinations that are above 30K, while for sources having NH\(_3\) (1,1), (2,2) and (3,3), 28 % of the sources have
kinetic temperatures above 30K which is comparable to the 22% found by Hill et al. (2010) for their sample of ammonia toward massive star forming regions. Hill et al. (2010) find a median kinetic temperature of 20K for their population of objects which is somewhat lower than the result here. The ambiguity in kinetic temperature determinations above 20K may play a part in the range of temperatures found from Hill et al. (2010) and Wu et al. (2010) in comparison to this work. Hill et al. (2010) predict upper and lower values for their kinetic temperature estimates, for kinetic temperatures less than 20K they found the upper and lower estimates well contrained with the derived kinetic temperature, however for sources with kinetic temperatures > 20K the upper limits can be greater than 100K in some sources. The kinetic temperatures were derived using the same procedure in this work, Hill et al. (2010) also used Parkes in their NH$_3$ observations, it is then reasonable to assume that in the kinetic temperatures estimated in this analysis will also have large uncertainties. To compare if there is any difference between the kinetic temperatures for sources with and without NH$_3$ (3,3) emission a KS test was performed. The results suggest that the sources are from a different population of objects, however, the confidence level of 0.7 is not high enough to state this unequivocally.

### 4.3.6 Kinetic Temperatures and NH$_3$ Line Widths

Line widths can give an indication into the internal motions of the gas, the comparison of the NH$_3$ (1,1) line widths to the corresponding kinetic temperature determinations is shown in Figure 4.22. There appears to be a trend of increasing NH$_3$ (1,1) line widths with increasing kinetic temperature. The sources with NH$_3$ (3,3) detections also appear to typically have average broader 3.05 kms$^{-1}$ line widths and higher average kinetic temperature of 28K compared to the sources without (3,3) emission with average NH$_3$ (1,1) line widths of 2.26 kms$^{-1}$ and an average kinetic temperature of 23K. To investigate the nature of the broadening and its dependence on the increasing kinetic temperature the level of thermal broadening expected for a given temperature
4.3: INVESTIGATION OF PARKES DATA

Figure 4.22: Comparison of the NH$_3$ (1,1) line widths to the corresponding kinetic temperatures. The kinetic temperatures were estimated using equation 4.3. The dashed line is the contribution to the NH$_3$ (1,1) line width from thermal broadening, derived from the kinetic temperatures using Equation 4.4. The red triangles represent sources with NH$_3$ (1,1) and (2,2) emission and no detected (3,3) emission, the blue circles correspond to sources that have detections in the NH$_3$ (1,1), (2,2) and (3,3) transitions. The error bars for the NH$_3$ (1,1) line widths were provided by the CLASS fits.

is calculated using equation 4.4 (Pillai et al. 2006),

\[
\Delta \nu_{th} \sim \sqrt{\frac{8 \ln(2) k T_{kin}}{m_{NH_3}}},
\]

where \(\Delta \nu_{th}\) is the contribution of thermal broadening to the line width given the kinetic temperature \(T_{kin}\) of the gas, \(k\) is the boltzman constant and \(m_{NH_3}\) is the mass of the ammonia molecule. The derived values of \(\Delta \nu_{th}\) are displayed as a dashed line in Figure 4.22, it is clear from Figure 4.22 that the increase in line widths cannot be solely attributed to the effects of thermal broadening as the kinetic temperature in-
Figure 4.23: Comparison of the NH$_3$ (3,3) line widths to the corresponding kinetic temperatures. The kinetic temperatures were estimated using the properties of the (1,1) and (2,2) emission in Equation 4.3.

The broadening could then be due to the turbulence or systematic effects of the region. Figure 4.23 shows the line widths of the NH$_3$ (3,3) emission against the corresponding kinetic temperature estimates. There is no apparent correlation in Figure 4.23 between the NH$_3$ (3,3) line widths and the kinetic temperatures. This is not surprising as the kinetic temperatures were derived using the properties of the NH$_3$ (1,1) and (2,2) emission, which are at lower temperatures than the NH$_3$ (3,3) emission. To derive reasonable kinetic temperature estimates, relating to the gas of the higher energy NH$_3$ transitions would require using the properties of the higher energy transition such as the NH$_3$ (3,3) with the NH$_3$ (4,4) emission, due to time limitations the NH$_3$ (4,4) (which was observed with Parkes simultaneously along with the NH$_3$ (1,1), (2,2) and (3,3) transitions) has not yet been reduced.
4.4: COMPARISON OF THE PARKES AND MOPRA DATA

4.4.1 NH$_3$ and CS Line Widths

The line widths of the NH$_3$ (1,1) transition are compared to the FWHM of the CS emission in Figure 4.24. The CS line widths are found to broader than the NH$_3$ (1,1) line widths. This result is typically also found in previous work by Anglada et al. (1996). Anglada et al. (1996) typically find that the CS line widths are related to the NH$_3$ (1,1) line widths through the linear fit,

$$\Delta V(CS) = 1.1\Delta V(NH_3) + 0.3.$$  (4.5)
As the slope is \(\sim\) unity they conclude that the difference is best described as an additive term, which for their relation is 0.3 \(\text{kms}^{-1}\). This suggests possibly that the difference may be due to more turbulent regions traced by the CS, or that the CS is tracing larger regions. In Figure 4.24 the line widths of the CS are found to have a mean of 4.65 \(\text{kms}^{-1}\) compared to the \(\text{NH}_3\) (1,1) line widths of 2.69 \(\text{kms}^{-1}\). The linear fit to the data is shown in Figure 4.24 and is found to have a relation,

\[
\Delta V(\text{CS}) = 0.98\Delta V(\text{NH}_3) + 1.96. \tag{4.6}
\]

This gradient is then approximately unity corresponding to the slope in Equation 4.5, the additive term is found to be considerably higher at 1.96 (as in 4.6) than the value of 0.3 found by Anglada et al. (1996). The higher broadening could possibly be attributed to higher turbulence in the regions surveyed here, with the association of the Class I emission to outflows increasing the line widths. Anglada et al. (1996) target regions traced by H$_2$O maser emission which is also known to trace outflows, the H$_2$O maser however, is also known to trace low and intermediate mass star formation which would be tracing less turbulent regions as opposed to only massive star forming regions traced by Class II CH$_3$OH in this research.

Figure 4.25 compares the line widths of the \(\text{NH}_3\) (1,1) and (3,3) emission to the corresponding CS FWHM, for those sources detected at 5\(\sigma\) or greater in \(\text{NH}_3\) (1,1), (3,3) and CS. There are only 59 sources that have both \(\text{NH}_3\) (3,3) and CS emission in comparison to Figure 4.24 displaying 124 sources with both CS and \(\text{NH}_3\) (1,1) detections. The average CS line widths are found to be 5.6 \(\text{kms}^{-1}\), the \(\text{NH}_3\) (1,1) and (3,3) have line widths of 3.1 \(\text{kms}^{-1}\) and 4.5 \(\text{kms}^{-1}\) respectively. It is clear from Figure 4.25 that the \(\text{NH}_3\) (3,3) line widths have a more closely associated correlation to the CS emission than the \(\text{NH}_3\) (1,1) emission. Implying that the \(\text{NH}_3\) (3,3) emission is possibly tracing a similar gas within the molecular clouds. The linear fit for the \(\text{NH}_3\) (3,3) and CS line widths is found to have a gradient of 0.77 and an offset similar to the CS and \(\text{NH}_3\) (1,1) offset.
4.4.2 \( \text{NH}_3 \) (1,1) Line Widths With Associated Class I Emission

Comparing the \( \text{NH}_3 \) line widths of sources with and without detected Class I methanol maser emission can give an insight into the internal dynamics of the regions, to help understand if any differences do exist between the two populations. The \( \text{NH}_3 \) (1,1) line widths for sources with detected Class I emission and those sources without any associated Class I emission are displayed in the upper and lower panels of Figure 4.26 respectively. From the 124 sources detected with \( \text{NH}_3 \) (1,1) and corresponding CS emission, 98 sources have Class I detections with 26 sources displaying no Class I emission. When comparing the two samples it is found that the mean \( \text{NH}_3 \) (1,1) line widths for sources with corresponding Class I maser emission is 2.74 kms\(^{-1}\) which
is broader than sources containing no detected Class I maser emission, on average by $\sim 0.22 \text{ km s}^{-1}$ (which is interestingly the expected thermal broadening contribution for a kinetic temperature of 20K). The broadening could be attributed to the more likely turbulent nature of the sources with Class I detections due to associated outflows. The limitations on the resolution, however make it difficult to place firm constraints on exactly what region the ammonia is tracing within the cloud and what manner of turbulence is possibly contributing to the broadening. The difference between the two populations could again be possibly attributed to the evolutionary state indicating that the regions with Class I emission and broader line widths are tracing more evolved objects.

To check if there is any significance in the difference of the NH$_3$ (1,1) line widths
for sources with and without associated detected Class I emission a KS test was performed on the two populations. The KS rejected the hypothesis that the two samples are from the same population of objects, implying that sources with and without Class I emission are possibly tracing different environments, however the confidence level is only 0.77. For sources with NH$_3$ (1,1) and (2,2) the sample size drops to 86 with only 9 sources not detected in Class I, and when considering sources detected in all three transitions again the sample size is reduced to 59 sources with only 5 having no associated Class I emission. Comparing the line widths of the NH$_3$ (2,2) transition for sources with and without Class I maser detections the mean is found to be 3.12 kms$^{-1}$ and 2.42 kms$^{-1}$ respectively. Whereas the average line widths of the (3,3) emission for sources with and without Class I detections are 4.59 kms$^{-1}$ and 4.51 kms$^{-1}$ which is comparable, however, comparison between the detected and non detected sources is difficult due to the low number of sources with no detected Class I emission.

**NH$_3$ (1,1) Line Widths and Kinetic Temperatures with Class I Emission**

To gain a further understanding of the nature of the differences in the line widths between sources with and without Class I emission, the NH$_3$ (1,1) line widths are compared with their respective kinetic temperatures for sources with and without Class I emission, which can be seen in Figure 4.27. The sources with and without Class I emission both have a mean kinetic temperature of $\sim$ 27K. A KS test on the kinetic temperatures for sources with and without Class I maser detections, produces a confidence level of 0.88 that the two groups are from a different set of objects. There are, however, only 9 sources that do not have an associated Class I maser, but have emission in the NH$_3$ (1,1) and (2,2) transitions required to make kinetic temperature estimates.

**4.4.3 Comparison of the Higher Flux Class I Masers**

For sources with detected Class I emission, it is interesting to see if there is any variation of the kinetic temperatures in relation to the Class I to Class II flux ratio. Figure
4: RESULTS AND ANALYSIS

Figure 4.27: Comparison of the NH$_3$ (1,1) line widths and corresponding kinetic temperatures. The kinetic temperatures were estimated using equation 4.3. The dashed line represents the contribution to the NH$_3$ (1,1) line width from thermal broadening, derived from the kinetic temperatures using Equation 4.4. The sources with a Class I detection are represented by red circles whereas sources with no detected Class I maser emission are displayed as blue triangles.

4.28 displays the logarithm of the Class I to Class II flux ratio against the kinetic temperature, there appears to be no discernable correlation in the distribution.

NH$_3$ Line Widths

Considering the split in flux ratio made in Section 4.2.7, Figure 4.29 displays the kinetic temperature and corresponding NH$_3$ (1,1) line widths for sources with a Class I to Class II flux ratio $> 5$ compared to sources with a Class I to Class II flux ratio $< 5$. From Figure 4.29 the line widths of sources with a Class I to Class II flux $> 5$ appear narrower than those with a ratio $< 5$. The average NH$_3$ (1,1) line widths are found to
4.4: COMPARISON OF THE PARKES AND MOPRA DATA

Figure 4.28: Kinetic temperature in comparison to the logarithm of Class I to Class II peak flux ratio, for those sources that have detections in NH$_3$ (1,1) and NH$_3$ (2,2) emission required for the kinetic temperature estimates.

be 2.88 kms$^{-1}$ and 2.59 kms$^{-1}$, for flux ratios < 5 and > 5 respectively. The sources with Class I emission greater than the Class II emission have on average narrower NH$_3$ (1,1) line widths, which could mean they are inhabiting less turbulent regions, than sources where the Class I to Class II ratio is less than 5. There appears to be a trend for both groups with increasing NH$_3$ (1,1) line widths with increasing kinetic temperatures. The average kinetic temperatures are found to be $\sim$ 27K for sources with a flux ratio < 5 and > 5. KS tests on the two sample groups was performed for the kinetic temperature and line widths of the NH$_3$ (1,1) transitions, for both parameters the sources in respective samples were found to be from different objects. The likelihood that they are tracing different objects, however, for both the kinetic temperature and line width is only at a confidence level of 0.78.
Class I Velocity Structure in Comparison with Kinetic Temperature Estimates

Sources with a Class I flux greater than the Class II flux on average appear less turbulent than those with lower flux ratios, considering the association of the Class I maser emission with the outflow regions it is interesting to also compare the Class I line width structure to the kinetic temperature. Figure 4.30 displays the Class I line widths in respect to their corresponding kinetic temperatures. The sources are again split into sources with a Class I to Class II flux ratio greater (blue circles) and less than (red circles) 5. There appears to be a slight correlation in Figure 4.30 with increasing line widths towards higher kinetic temperatures. The average Class I line widths are found to be 7.66 km s\(^{-1}\) and 9.73 km s\(^{-1}\) for sources with Class I to Class II flux ratios >5 and <5 respectively. The relationship of sources with Class I to Class II flux ratios > 5 having narrower line widths is in agreement with the NH\(_3\) (1,1) line widths and also the relation seen in Figure 4.13 for the average CS line widths. A KS test on the Class I line widths for both samples again finds that the two flux ratio groups are from a different set of objects, however, the confidence is again only 0.78.

4.5 Properties Throughout the Galactic Plane

Understanding if the environments of the Class II CH\(_3\)OH masers vary over the Galactic plane is of interest because of the potentially varying star forming environments in the plane. The sources observed at Mopra and Parkes were selected from the MMB survey to sample sources over different spiral arms of the Galaxy allowing the environments to be explored further. A summary of the regions observed and the corresponding number of sources detected at 5\(\sigma\) or greater in CS emission is shown in Table 4.8. Figure 4.31 displays the CS line widths as a function of Galactic longitude, the associated regions are also shown. The Centaurus region displays less spread in CS line width values, there also appears to be a trend of increasing line width values across the 3kpc arm. Figure 4.32 displays the mean and median values of the CS line
widths divided into the bins based on their region. The Centaurus region is found to have the smallest mean and median CS line width values. The sources with Class I detected maser emission (red circles and triangles) are broader over the whole Galactic plane than those sources with no detected Class I emission. The miscellaneous region (40–50 degrees) shows a large offset between mean and median values of the CS line widths for sources with and without Class I maser emission. On further inspection 3 of the sources having the largest CS line widths are within this region and are also the sources that were selected in Section 4.2.1 as potential blended emission candidates, but were subsequently unable to be fitted with multiple Gaussians. The mean line widths of sources detected with Class I maser emission range from $\sim$4–5 kms$^{-1}$, sources with no Class I maser emission are typically have CS line widths 1 kms$^{-1}$ nar-
Figure 4.30: Class I velocity coverage in comparison to the kinetic temperatures for sources that have Class I to Class II peak flux ratios of greater than 5 (blue triangles) and sources that have a flux ratio less than 5 (red circles).

rower ranging between $\sim 3$–$4 \text{ kms}^{-1}$. There appears to be a slight correlation with increasing mean and median CS line width values from Galactic longitudes of $-60$ to $60$ degrees. The nature of this is unclear and will be explored further in the near future.

Figure 4.33 compares the mean and median values of the logarithm flux ratio of the Class I emission to the Class II emission as a function of Galactic longitude, weighted in bins by region. The mean and median values for each region are seen to have large offsets indicating outliers. The mean and median values of the logarithm of the flux ratio range from $\sim -0.2$ to $0.4$ (corresponding to a Class I to Class II flux ratio ranging from $\sim 0.6$ to $2.5$). The biggest difference comes from sources in the 3kpc arm ($-15^\circ \rightarrow 15^\circ$) and those in the Centaurus tangent ($-45^\circ \rightarrow -55^\circ$). Exploring these two regions further the Centaurus tangent is found to have the two brightest Class I masers,
Figure 4.31: CS line widths as a function of Galactic longitude. The dashed lines indicate different regions of the Galaxy (Table 4.8) with the names of the corresponding regions displayed. The red circles represent sources that have associated Class I maser detections, the blue circles represent sources that display no Class I maser emission at $\geq 5\sigma$. whereas the 3kpc arm contains the source having a Class I to Class II flux ratio of $> 80$. To understand if there is any significance in the variation of the flux ratio over the galactic plane, distance estimates would be needed. Due to time limitations it was not possible to follow up any of these initial results, an interesting aspect would be looking at temperature distributions from kinetic temperature estimates, which will be completed in the near future.
Table 4.8: Number of sources detected at $5\sigma$ or greater in the CS over longitude ranges over the galactic plane, along with details of those sources detected with and without Class I masers.

<table>
<thead>
<tr>
<th>Region</th>
<th>Galactic range</th>
<th>Number of sources detected at $\geq 5\sigma$ in CS</th>
<th>Number of sources detected at $\geq 5\sigma$ in CS and Class I emission</th>
<th>Number of sources detected at $\geq 5\sigma$ in CS and $&lt;5\sigma$ in Class I emission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centaurus tangent</td>
<td>-55 $\rightarrow$ -45</td>
<td>40</td>
<td>27</td>
<td>13</td>
</tr>
<tr>
<td>Norma tangent</td>
<td>-25 $\rightarrow$ -20</td>
<td>72</td>
<td>49</td>
<td>23</td>
</tr>
<tr>
<td>Scutum tangent</td>
<td>20 $\rightarrow$ 35</td>
<td>63</td>
<td>42</td>
<td>21</td>
</tr>
<tr>
<td>3 kpc arm</td>
<td>-15 $\rightarrow$ 0 $\rightarrow$ 15</td>
<td>30</td>
<td>22</td>
<td>8</td>
</tr>
<tr>
<td>misc$^a$</td>
<td>40$\rightarrow$50</td>
<td>11</td>
<td>4</td>
<td>7</td>
</tr>
</tbody>
</table>

$^a$This region was not originally proposed for observation but these sources were observed in the additional time that was available.
Figure 4.32: CS line widths as a function of Galactic longitude. The mean and median CS line widths and Galactic longitude for all sources in each of the 5 regions given in Table 4.8 have been calculated, the mean and median of the CS line widths and corresponding mean Galactic longitude of sources with detected Class I emission are represented by red circles and triangles, whereas the corresponding mean and median CS line widths for sources with no detected Class I emission are represented by blue circles and triangles respectively.
Figure 4.33: Logarithm of the Class I to Class II flux ratio (for sources detected at $\geq 5\sigma$ in Class I maser emission) as a function of Galactic longitude. The mean (circles) and median (triangles) Class I to Class II flux ratios along with the corresponding mean and median Galactic longitude for all sources in each of the 5 regions described in Table 4.8 are shown.
5

Discussion and Conclusion

This dissertation has looked at the properties of the molecular environments of massive star forming regions traced by 6.7 GHz Class II CH$_3$OH masers. Chapter 4 analysed the molecular emission from the Parkes and Mopra observations to explore the 6.7 GHz Class II maser environments further. Section 5.1 discusses and summarises the results from Chapter 4, Section 5.2 describes the analysis that due to time constraints has not yet been completed, along with describing further observations that could be undertaken that would potentially provide important additional information.

5.1 Discussion

5.1.1 NH$_3$ Line Widths

The variation of NH$_3$ (1,1) line widths between previous surveys targetting massive star forming regions (which is summarised in Table 4.4) is large. It has been suggested that the variation in the structure of the NH$_3$ (1,1) line widths potentially represents an evolutionary sequence in massive star forming regions (Sridharan et al. 2005). Narrower NH$_3$ (1,1) line widths are found toward earlier less turbulent stages such as IRDCs (Pillai et al. 2006) and high mass starless cores (Sridharan et al. 2005) in comparison to broader NH$_3$ (1,1) line widths detected toward more evolved regions such
as UCHII regions (Churchwell et al. 1990). The average NH$_3$ (1,1) line widths in this dissertation were found to be between the average values determined by Sridharan et al. (2002) observing massive protostellar objects and those values found by Churchwell et al. (1990) when surveying UCHII regions. Which may suggest that the objects observed in this work lie at an evolutionary stage between the very early stages of protostellar formation and the more evolved UCHII stage. This suggestion is reasonable and consistent with previous observational and theoretical work on Class II CH$_3$OH maser emission. Accretion discs in the early phases of protostellar collapse are found to produce temperatures sufficient to release CH$_3$OH from dust grains (Cragg et al. 2005), colder evolutionary stages such as IRDCs and high mass starless cores would not produce sufficiently high temperatures to release large amounts of CH$_3$OH required for maser emission. Observationally Class II methanol masers have not been observed toward HII regions (Minier et al. 2005) and are not prevalent toward UCHII regions (Pandian et al. 2010).

5.1.2 NH$_3$ Toward Class II Masers

Interestingly when considering surveys of NH$_3$ toward objects traced specifically by Class II emission Wu et al. (2010) found differences between the NH$_3$ line widths of the low and high luminosity Class II masers. They found that the higher luminosity Class II masers have broader NH$_3$ (1,1) line widths. This may be indicating that higher luminosity Class II masers are at a more evolved stage than lower luminosity masers. The NH$_3$ (1,1) line widths in this research are found to be in between the low and high luminosity values found by Wu et al. (2010). Assuming that the evolutionary scenario for NH$_3$ line width broadening is valid, this is not completely surprising as Wu et al. (2010) surveyed a biased sample of low and high luminosity maser emission, whereas this research is analysing unbiased observations of Class II masers which would be expected to contain a distribution of Class II CH$_3$OH maser luminosities.

The Longmore et al. (2007a) sample of hot molecular cores traced by Class II
emission used the high resolution of ATCA to map the NH$_3$ emission, this enabled them to separate the NH$_3$ into cores. Longmore et al. (2007b) split the NH$_3$ cores observed by Longmore et al. (2007a) into groups, suggesting that the association of Class II and 24 GHz continuum emission with the cores again suggests an evolutionary sequence which is evident in the NH$_3$ (1,1) line widths. The more quiescent cores, that have no Class II or 24 GHz continuum emission have the narrowest NH$_3$ (1,1) line widths, cores associated with Class II maser emission have broader line widths and again further broadening is seen towards NH$_3$ cores with Class II and 24 GHz continuum emission. Cores found to have no association to 24 GHz continuum or Class II maser emission have values comparable with those found for IRDCs. Interestingly the average NH$_3$ (1,1) line widths in this research are found to lie between the line widths of NH$_3$ cores found to be traced by only Class II emission, and those cores found to have both Class II and 24 GHz continuum emission. This suggests that the objects observed in this work are on average found to be at a stage after the very earliest stage of collapse and typically before the formation of an UCHII region. Without observing continuum emission or molecular lines tracing cold gas and obtaining accurate temperature determinations it is difficult to make firm conclusions about the evolutionary stage of individual objects surveyed here.

5.1.3 NH$_3$ (1,1) and (2,2) Emission

The average NH$_3$ (1,1) and (2,2) line widths have different values, with the NH$_3$ (2,2) emission typically displaying broader line widths. This increase in the NH$_3$ (2,2) line widths is similarly seen by Wu et al. (2010), Pillai et al. (2006) and Hill et al. (2010), with Pillai et al. (2006) suggesting that the two transitions may not be tracing the same gas within the region. In contrast to this suggestion Longmore et al. (2007a), find that the NH$_3$ (1,1) and (2,2) have similar morphology inferring that they are tracing the same gas region. In comparison to the single dish observations incorporating the entirety of the extended NH$_3$ (1,1) and (2,2) emission used in this research, Longmore
et al. (2007a) use ATCA with a resolution of 11″ which allowed them to split the ammonia emission up into cores. On smaller scales it is likely that the changes in line widths will be less prevalent than the effects of surveying over the whole region on a larger scale.

### 5.1.4 \textit{NH}_3 (3,3) Emission

The higher energy \textit{NH}_3 (3,3) transitions display considerably larger line widths than either the \textit{NH}_3 (1,1) or (2,2) emission. Longmore et al. (2007a) also observe this broadening toward the higher energy \textit{NH}_3 transitions in their survey. They suggest that the broadening cannot be purely attributed to thermal broadening and may influenced by systematic effects of rotation, infall and/or outflows, or possibly from increased levels of turbulence in the regions associated with the higher energy emission. The \textit{NH}_3 (3,3) transitions are at temperatures of 120K above the ground state compared to the \textit{NH}_3 (1,1) and (2,2) emission at temperatures of 23K and 64K above the ground state. The \textit{NH}_3 (3,3) emission, is therefore tracing the warmer gas regions located closer to the central protostellar object. As mentioned above the increase in line widths is not likely to be solely influenced by the effects of thermal broadening, other effects must then be influencing the line widths of the \textit{NH}_3 (3,3) emission, but without higher resolution it is difficult to constrain what structure within the region the \textit{NH}_3 (3,3) emission is tracing. For sources that have detected \textit{NH}_3 (3,3) emission the average line widths of the \textit{NH}_3 (1,1) emission are broader in comparison to sources with no \textit{NH}_3 (3,3) emission, suggesting that the sources with detected \textit{NH}_3 (3,3) emission are indeed more turbulent than those sources detected without any associated \textit{NH}_3 (3,3) emission.

### 5.1.5 Comparison of CS and \textit{NH}_3 Line Widths

The CS to \textit{NH}_3 (1,1) line widths have a similar linear fit to Anglada et al. (1996), having a gradient of unity, with a much larger offset at nearly 5 times the value seen
by Anglada et al. (1996). This suggests that the regions traced here are more turbulent in the CS than those found by Anglada et al. (1996), but follow a similar linear relationship with the NH$_3$ (1,1) emission. The regions here are likely to be more turbulent than those observed by Anglada et al. (1996) as the Anglada et al. (1996) sample are possibly tracing low and intermediate star forming regions as well as massive star formation. The average line width of sources with NH$_3$ (3,3) emission is found to be comparable with the average values of CS line width. The CS line widths are found to be on average broader for sources containing both CS and NH$_3$ (3,3) emission, in comparison to the average values of the CS line widths when considering the whole CS sample. This suggest again that sources containing NH$_3$ (3,3) emission are more turbulent. The linear correlation between the CS and NH$_3$ (3,3) line width, however, has a gradient of 0.77. For sources with NH$_3$ (3,3) line widths <4 km$s^{-1}$ there appears to be a more closely associated correlation between the CS and NH$_3$ line widths. This would need to be investigated further, however it possibly suggests that in less turbulent regions the line widths of the NH$_3$ and CS will be more closely related, it would be interesting to map these regions in comparison to the sources with larger line width values in both, to determine exactly what they are tracing in the regions. It is possible that they are tracing multiple sub-structure along the line of sight increasing the line widths.

### 5.1.6 Class I and Class II CH$_3$OH Maser Detection Rates

An underlying aim has been to explore those sources that have associated Class I CH$_3$OH maser emission and understand if distinctions exist between those sources that are not detected with any associated Class I maser emission. The detection rate of Class I masers toward Class II masers is found to be ~66%, which differs significantly with other known observational results of Class I masers toward Class II masers (e.g. Fuller et al. 2011, Val’tts & Larionov 2007 and Cyganowski et al. 2009). On closer inspection differences between sensitivity limits and the spatial extent of the region that
an association is classed, appear to be the main causes of the discrepancies. Changing sensitivity limits and the size of the region that is classed to be a detection, then give comparable detection rates, with the exception of surveys that have a strong bias toward sources more likely to trace Class I maser emission such as EGOs (Cyganowski et al. 2009). The Class I CH$_3$OH maser emission is known to be weaker than the 6.7 GHz Class II CH$_3$OH maser emission. The question then remains if there is a percentage of Class II sources in an evolutionary stage without the presence of a Class I maser or if the detection rate is due to sensitivity limitations. Class I masers form at a greater offset from the central region $>10^4$ AU than Class II (Marseille et al. 2010), for the Mopra observations of the Class I masers used in this research a resolution of $\sim2\times10^4$AU is obtained at 0.4 kpc. Higher resolution pointed observations of massive star forming regions at relatively close distances may then potentially miss the Class I emission. Contrary to this, lower resolution observation at larger distances will be typically observing larger regions incorporating emission that may not be associated with the protostellar object that the Class II emission is tracing. Without distances to sources and only pointed observations it is difficult to estimate to what extent sensitivity limits or resolution effects may be influencing the detection rate. Mapping the regions at higher resolution would provide constraints on the extent to which the Class I emission is offset from the central protostellar objects, providing valuable information on the exact spatial relation of the Class I emission to the Class II emission and how this varies with environmental properties.

For the Mopra data 66 % (144 out of 216) of the sources are detected with CS and Class I maser emission at $\geq5\sigma$. Interestingly considering the sources observed at Parkes 79 % of the sources (98/124) are detected in NH$_3$ (1,1) and Class I maser emission at greater than $5\sigma$, which increases to 88 % for NH$_3$ (2,2) and 91 % for NH$_3$ (3,3) emission and Class I maser emission at greater than $5\sigma$. This suggests that NH$_3$ observations are more likely to be tracing regions containing both Class I and Class II emission with the higher energy NH$_3$ transitions more likely to be tracing both classes. The total number of sources observed at Parkes was however smaller than the
sample observed at Mopra, the higher detection rate could be due to more of the sources containing Class I emission being selected in the Parkes sample, without observing the total number of sources sampled by Mopra it is difficult to make an inference on the differences in the detection rates.

5.1.7 Line Widths of Sources With and Without Class I Maser Detections

The CS line widths of sources with Class I emission are found on average to be slightly broader than sources displaying no detected Class I emission, the KS test however, reveals no evidence that they are from different populations. This same result is seen when comparing the line widths of the NH$_3$ emission only a slight broadening is seen toward sources with Class I emission, with a KS test not providing a strong confidence level that they are from different objects.

The Class I emission is known to be tracing the outflow, the ratio of the Class I velocity structure to the CS FWHM suggest that for 70% of the sources the CS and Class I maser emission could be related, suggesting that the CS emission may also be influenced by the outflow.

5.1.8 Class II and CS Flux

Sources with and without detected Class I CH$_3$OH maser emission, have both on average higher Class II and CS flux values for those sources associated with Class I maser emission, however the confidence level found by the KS test that they are from different populations is not substantial. Distance estimates will be available in the near future allowing the luminosities of the CS and Class II maser emission to be determined. This will be particularly interesting to see if there is any relation between sources with and without Class I emission. The Class II maser is known to be variable, the variation in the Class II maser emission may also be influencing the Class II intensities, along with the Class I to Class II flux ratios.
5.1.9 Class I and Class II Flux

It has been suggested that an evolutionary sequence exists between Class I and Class II emission. The flux ratio of the peak of the Class I to the peak Class II flux was investigated. A comparable number of sources were found to have flux ratios greater and less than 1. The CS line widths of the two groups were found to show no evidence of any difference. Interestingly some sources are found to have a Class I peak flux of greater than 80 times the Class II flux. Pratap et al. (2008) believe the flux ratios of different Class I maser transitions provides evidence for an evolutionary transit suggesting that a flux ratio of 5 distinguishes between earlier and later evolutionary stages within the Class I maser transitions. Considering this ratio for the Class I to Class II emission 17% of sources have a Class I peak flux greater than 5 times the Class II peak flux. The CS line widths are found to be broader for sources that have a Class I to Class II peak flux ratio less than 5. The KS test provides only a confidence of 0.8 but in comparison to the flux ratio of 1 where the KS test showed no evidence that they were from the same population the results may have some significance. The NH$_3$ (1,1) line widths also appear narrower for Class I sources with a ratio greater than 5. Considering the proposed evolutionary sequence suggested previously for the NH$_3$ (1,1) line widths, this is a possible indication again that the sources with higher Class I peak flux values compared to the Class II emission are less turbulent and at an earlier evolution. Sources with Class I emission stronger than the Class II emission may then be less turbulent, which may imply that they are indeed in an earlier evolutionary state as suggested by Ellingsen et al. (2007). The Class I velocity coverage, which is tracing some part of the outflow structure shows only a slight correlation with the Class I to Class II flux ratio, with a smaller velocity coverage found for sources that are displaying higher Class I to Class II ratios. This may indicate that for sources with brighter Class I emission the outflows are less turbulent indicating again an earlier evolution, but is difficult to constrain exactly what part of the outflow is being traced by the Class I emission. The possible effects of Class II flux variance and possibly variability in the
5.2: FUTURE WORK

Class I maser emission need to be considered. It would also be interesting to observe the sources having Class I peak flux at greater than 20 times the Class II peak flux at higher resolution to understand what spatial relation these bright Class I masers have in comparison the the Class II masers.

5.1.10 Properties Over The Galactic Plane

The possible variation of the Class II maser environments was only initially investigated. There appears to be a possible trend in increasing CS line width values over the Galactic plane. Lower CS line widths are observed at the Centaurus region at $-55^\circ$ $\rightarrow -45^\circ$ and slightly increase over the Galactic plane with larger values observed in the miscellaneous region at $40^\circ$ $\rightarrow 50^\circ$. The nature of this possible correlation is unclear, distances to sources would be particularly useful to explore this further. There is a large variation in Class I to Class II flux ratios over the Galactic plane, again without distances it is difficult to understand fully if this is due to intrinsic differences in the environments of the sources within the regions.

5.2 Future Work

Due to time limitations the analysis is not yet fully complete, there still remain some interesting properties that can be explored further. It was only possible for the CS, Class I and NH$_3$ (1,1), (2,2) and (3,3) transitions to be reduced and analysed, there still remains some interesting molecular lines observed with Parkes and Mopra that will be reduced in the near future. Section 5.2.1 describes the analysis that given the time limitations was not possible to complete and will be done in the near future. Section 5.2.3 describes further observations that would be interesting to complete.
5.2.1 Future Work on The Analysis

The optical depths of the NH$_3$ (1,1) transition are provided by the CLASS fits, using this in conjunction with the rotational temperature estimates made in Section 4.3.5 it is possible to derive estimates for the NH$_3$ column densities (Ungerechts et al. 1986). Using these derived NH$_3$ column densities in conjunction with CS column densities could allow for the coldest and possibly earliest sources to be found in the sample. CS is found to freeze out onto dust grains more readily than the NH$_3$ molecule (Bergin & Langer 1997), hence a column density ratio of NH$_3$ to CS should provide evidence of colder gas. The CS J=1-0 transition is optically thick, however, the observations done at Mopra also include the rarer isotope $^{13}$CS, using the CS and $^{13}$CS transitions it is possible to estimate the CS column density. Comparing the flux ratios of the expected coldest and youngest sources could provide evidence if the CH$_3$OH masers do have an evolutionary sequence that is related to the corresponding flux ratios of different transitions.

An underlying goal of this research is to explore the variance in the Class II masers over the Galactic plane. This was only initially investigated in Section 4.5. In future analysis the properties of the NH$_3$ emission and the derived kinetic temperatures, along with column density estimates will be explored.

Distances to the Class II masers in the MMB survey will become available in the near future. This would allow luminosity determinations to be made on maser emission. It could also help understand the detection rates of the Class I maser emission toward the Class II maser emission. This would allow the sensitivity and/or resolution influences on the detection rates to be explored further.

5.2.2 Reduction of Molecular Lines

As mentioned above the rarer isotope of the CS molecule $^{13}$CS will be used to estimate CS column densities. Within the Mopra observations there are also some other molecular lines that would be particularly useful, such as SO$_2$ which is known to trace
5.2: FUTURE WORK

outflows, allowing the structure of the outflow to be investigated and understand further if their is any relation in the outflow size and the Class I emission.

The NH$_3$ (4,4) transition was simultaneously observed at Parkes along with the NH$_3$ (1,1), (2,2) and (3,3) transitions. Reducing the NH$_3$ (4,4) line would be particularly useful to estimate kinetic temperatures of the warmer gas. The NH$_3$ (3,3) and (4,4) emission trace warmer regions more closely associated to the central protostellar object than the NH$_3$ (1,1) and (2,2) emission, which is thought to be tracing the more extended envelope. The temperatures estimated in Section 4.3.5 derived using the properties of the the NH$_3$ (1,1) and (2,2) transitions are only reliable for kinetic temperature estimates where the gas is at temperatures $< 30$K. In comparison the NH$_3$ (3,3) and (4,4) emission is at temperatures of $120$K and $200$K respectively allowing kinetic temperature estimates of the warmer gas more closely associated with the central regions. Recent work by Beuther & Walsh (2008) has used the NH$_3$ (4,4) emission to trace accretion discs around massive stars, the resolution of Parkes will not allow any information on velocity gradients of the (4,4) emission to be determined, however sources with bright NH$_3$ (4,4) emission could be singled out for future high resolution mapping observations.

5.2.3 Future Observations

Mapping positions of the Class I emission would provide constraints on the spatial coincidence of the Class I emission to the central protostellar object and the Class II masers. As suggestions have been made into an evolutionary sequence of the Class I to Class II emission understanding if the Class I offset has any relation to the peak intensity of the Class I and Class II emission may help understanding this proposed evolutionary sequence. Initial results from this work indicate that those sources with Class I emission do indeed appear to be more turbulent, the CS and NH$_3$ line widths are found to be broader for sources associated with Class I maser emission than for sources with no detected emission. Considering the Class I to Class II flux ratios
however, sources with Class I peak emission 5 times greater than the Class II peak maser emission appear to be less turbulent than sources where the Class I to Class II flux ration is $< 5$.

The (3,3) line widths are found to be considerably larger than the NH$_3$ (1,1) and (2,2) emission. Mapping the regions for NH$_3$ (3,3) emission at high resolution could identify the cause of this particularly large increase, understanding if there are additional NH$_3$ (3,3) filaments along the line of sight which would increase the (3,3) line widths or constrain what region of the core the emission is tracing and if it displays velocity gradients consistent with the systematic effects of infall/rotation or outflows.
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