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Insights into High Mass Star Formation from Methanol Maser Observations

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Insights into high mass star formation from methanol maser observations.

by

Hontas Freeman Farmer

A thesis submitted in partial fulfillment for the degree of Master of Science in the Department of Physics College of Science and Health

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We present high angular resolution data on Class I and Class II methanol masers, together with other tracers of star formation like H$_2$O masers, ultracompact (UC) ionized hydrogen (H II) regions, and 4.5 µm infrared sources, taken from the literature. The aim is to study what these data tell us about the process of high mass star formation; in particular, whether disk-outflow systems are compatible with the morphology exhibited by Class I and Class II methanol masers. Stars form in the dense cores inside molecular clouds, and while the process of the formation of stars like our Sun is reasonably well understood, details of the formation of stars with masses eight times that of our Sun or greater, the so-called high mass stars, remain a mystery. Being compact and bright sources, masers provide an excellent way to observe high mass star forming regions. In particular, Class II methanol masers are found exclusively in high mass star forming regions. Based on the positions of the Class I and II methanol and H$_2$O masers, UC H II regions and 4.5 µm infrared sources, and the center velocities ($v_{\text{LSR}}$) of the Class I methanol and H$_2$O masers, compared to the $v_{\text{LSR}}$ of the Class II methanol masers, we propose three disk-outflow models that may be traced by methanol masers. In all three models, we have located the Class II methanol maser near the protostar, and the Class I methanol maser in the outflow, as is known from observations during the last twenty years. In our first model, the H$_2$O masers trace the linear extent of the outflow. In our second model, the H$_2$O masers are located in a circumstellar disk. In our third model, the H$_2$O masers are located in one or more outflows near the terminating shock where the outflow impacts the ambient interstellar medium. Together, these models reiterate the utility of coordinated high angular resolution observations of high mass star forming regions in maser lines and associated star formation tracers.
Chapter 1

Introduction

Understanding the process of the formation of high mass stars with masses about eight times that of our Sun, or greater, remains a challenge in modern astronomy. High mass stars are important because they inject matter and energy into the interstellar medium of galaxies throughout their lifetimes. Observing high mass star formation is difficult, though, because massive star forming regions are farther away than their low mass counterparts, high mass stars form in clusters, and begin the process of nuclear fusion even as they are accreting matter. One of the key issues is whether high mass star formation is a scaled-up version of the low mass star formation process, complete with disk and outflows, or whether high mass stars form by coalescence of low mass stars. Being compact and bright sources, masers offer a unique opportunity to peer into the deep interior of high mass star forming regions at high angular resolution. In this thesis, we use data on methanol and water masers from the literature, along with other associated star formation tracers, to gain insight into the high mass star formation process by investigating whether disk-outflow systems are compatible with these maser data. In this chapter, we begin with a discussion of star formation in §1.1, and masers and maser observations in §1.2. In Chapter 2, we discuss the sources of our data. In Chapter 3, we present our results and discuss these results in Chapter 4. Finally, we state our conclusions in Chapter 5.

1.1 Star Formation

Stars form inside the densest regions of molecular clouds. Such clouds have temperatures from 10-50 K, particle densities, n(H$_2$), from 100-300 cm$^{-3}$, radii of 5-20 parsec (pc), and masses 10$^4$-10$^6$ $M_\odot$ (1pc $\equiv$ 3.26 Light Years — see Appendix A.4; 1 $M_\odot$ $\equiv$ 1.99 $\times$ 10$^{30}$kg, is the mass of our Sun). The dense cores inside these molecular clouds in which these
stars actually form have temperatures of 10 K, $n(\text{H}_2) \gtrsim 10^5 \text{ cm}^{-3}$, radii 0.01-1 pc, and masses $\sim 10 M_\odot$ (McKee & Ostriker 2007). Figure 1.1 is an example of such a molecular cloud (Ward-Thompson et al. 2007); the figure shows the Ophiuchus molecular cloud, together with its many star-forming cores (including cores in which there is no evidence of star formation at present). Two such cores are labeled in the figure. The filamentary structure seen in the figure is quite typical of molecular clouds, and is believed to be a result of their formation at the intersection of turbulent flows (Hennebelle & Falgarone 2012).

Figure 1.1: Image of the Ophiuchus molecular cloud taken with the James Clerk Maxwell telescope (JCMT) at 850 μm (Ward-Thompson et al. 2007). This example of a molecular cloud shows star-forming cores (including cores in which there is no evidence of star formation at present). Two such cores are labeled in the figure; VLA 1623 is a core with a star forming in it, and SMM1 is a pre-stellar core with no evidence of star formation. The axis labels (right ascension and declination) are standard in astronomical images, and are explained in more detail in Appendix A.1. Also, following the convention of astronomical images, east is to the left and west to the right.

Star formation begins when the dense cores within molecular clouds start to collapse. Stars with masses of 8 $M_\odot$ or higher are known as high mass stars, and their formation is known to be different from the formation of stars like our Sun (also known as low mass stars).
1.1.1 Low mass star formation

Over the last fifty years, astronomers have gained a fairly good understanding of the basic process of low mass star formation. Star formation is initiated when dense cores inside molecular clouds become gravitationally unstable and collapse. Depending on the size of the core, one or more stars will be formed. Small cores may form a single star, larger cores will fragment and form multiple stars (some authors use the term “clumps” for larger cores).

The exact details of the process of collapse are model dependent, but the following are generally common to most models (McKee & Ostriker 2007): Gravitational collapse builds up the central density in the core of the cloud or cloud fragment. The energy generated by the gravitational collapse is radiated away because the cloud remains optically thin (i.e., transparent to radiation); as a result, during the initial stages of the collapse, most models treat the cloud as isothermal. The isothermal collapse phase produces a central condensation of matter and ends with the formation of a stable object at the center called a protostar, surrounded by a gaseous envelope. With the increasing density in the gaseous envelope, it becomes harder for the energy released by gravitational contraction to escape from the star, as a result of which the internal temperature of the protostar rises. The protostar then enters its main accretion phase, in which it builds up its mass from a surrounding infalling envelope and accretion disk, even as it continues to get hotter. Some of the accreted material is ejected along opposite directions perpendicular to the accretion disk, and this is known as a bipolar outflow (e.g., see Figure 4.1). These outflows are believed to help in carrying away the excess angular momentum of the infalling matter; this is necessary because of the so-called “angular momentum problem” in star formation. This problem arises because while rotation is not a significant source of support in molecular clouds against gravity, a decrease of just a factor of 100 in size (while conserving angular momentum) increases the rotational energy to the point where it can support the cloud against gravitational collapse. Yet, since decreases by factors of $10^5$ or greater in size are required for a core to become a star, if it were the case that a decrease of just $10^2$ were enough to bring the rotational energy into equilibrium with gravitational energy, then stars could never form. Mechanisms have been sought for how to get rid of the angular momentum during collapse, and bipolar outflows and the magnetic fields that are present in these outflows are believed to carry away the excess angular momentum, but the exact mechanism is still not fully understood.

When the protostar has accumulated most of its final mass (that it will have during its lifetime as a main sequence star) it is generally known as a pre-main-sequence (PMS) star, although the use of the term varies among authors (McKee & Ostriker 2007).
Such stars continue to supply most of their luminosity (i.e., the energy output in, e.g., ergs s\(^{-1}\)) by contracting and releasing gravitational potential energy, but now their luminosities and surface temperatures increase. Eventually, the interior becomes hot enough to initiate hydrogen fusion, and this takes over as the cause of the luminosity of the star. The star soon comes into hydrostatic equilibrium between the outward thermal pressure and the inward gravitational pull and reaches its main sequence phase, in which it will spend 90\% of its life span, steadily fusing hydrogen to helium.

1.1.2 High mass star formation

The process of high mass star formation is not as well understood as low mass star formation. For a number of reasons high mass stars constitute a very difficult observational and theoretical problem. High mass star forming regions are located farther from us than low mass star forming regions; the nearest low mass star forming region is Ophiuchus at a distance of 120 pc (Loinard et al. 2008), whereas the nearest high mass star forming region in Orion is 500 pc away (Genzel et al. 1981); high mass stars usually form in clusters, and because of their high mass, they begin fusing hydrogen even as they are accreting material. It is difficult to find an isolated high mass star in the process of forming with which to study the process. If we observe an outflow, it is often difficult to figure out which high mass protostar the outflow is coming from, because the protostars are so close together. Moreover, high mass star forming regions are obscured by more gas and dust than low mass star forming regions (Zinnecker & Yorke 2007). Theoretical studies of this process must address how accretion can continue in the face of the tremendous outward radiation pressure generated by the onset of hydrogen fusion.

1.2 Maser observations of high mass star forming regions

Observations of maser lines are ideal for studying high mass star forming regions at high angular resolution, as masers are compact and bright sources. Below, we discuss what they are, a brief history of their observations, and why methanol masers are useful for the study of high mass star forming regions.

1.2.1 Astronomical masers

Masers were discovered before lasers and were named for Microwave Amplification by Stimulated Emission of Radiation (MASER). Masers are like lasers but they radiate at microwave (radio) wavelengths, and they involve excitation of molecular vibrational
modes instead of electronic energy levels. A diagram of maser energy levels is shown in Figure 1.2.

The key to maser operation is “population inversion.” To get a maser transition between energy states, we must have more molecules in the upper energy state (labeled as “upper meta-stable state” in Figure 1.2) than in the lower energy state. In practice, we need a short-lived high energy state into which the molecules can be pumped by infrared radiation or collisions. From this state, the molecules come down to the meta-stable state. This leads to a population inversion in which there are more molecules in the upper meta-stable state than the lower state. The molecules then decay by stimulated emission to the lower state. This is amplified as it goes through the masing medium, in this case, the interstellar molecular cloud. Amplification of this stimulated emission requires large scale velocity coherence through the masing medium. If there is too much turbulence, then the maser photons will scatter in random directions and amplification will not occur. Population inversion, stimulated emission, and amplification are thus the three major ingredients required for an astronomical maser. The pumping may be radiative (as in Class II methanol masers) or it may be due to collisions (as in Class I methanol and H$_2$O masers).

![Figure 1.2: Energy state diagram of a maser. The maser transition occurs via stimulated emission between the levels marked “upper meta-stable state” and “lower energy state.” In practice, molecules must be pumped into a short-lived high energy state from where they decay into the upper meta-stable state, to get population inversion between the upper meta-stable state and the lower energy state.](image-url)
1.2.2 A brief history of maser observations

The first observation of an astrophysical maser was by Weaver et al. [1965]. Since then maser lines have been observed in a variety of molecules like H$_2$O, SiO, CO, HCN, CS, and complex molecules such as CH$_3$OH. At first these observations were performed with single dish radio telescopes at angular resolutions on the order of arcminutes. Interferometers like the Very Large Array (VLA), and particularly the technique of Very Long Baseline Interferometry (VLBI), with many dishes spread out over a wide area, have allowed imaging of masers at sub-arcsecond resolution.

1.2.3 The methanol (CH$_3$OH) maser

Methanol masers occur in star forming regions. There are two varieties, with Class II masers exclusively associated with high mass star forming regions. The division into two classes was originally based on association: Class II masers are associated with protostars, and Class I masers are found in outflows (Menten 1991). Today, we know there are differences in the pumping mechanism as well; Class II methanol masers are believed to be radiatively pumped, while Class I masers are pumped collisionally. This would also explain why Class II masers are found near high mass protostars where they are pumped by the intense radiation from the protostar (Sobolev et al. 2006), and why Class I masers are found in outflows where they are pumped by collision at the interfaces of shock fronts between the outflowing material and the ambient interstellar material (Cragg et al. 1992). The most well known Class II methanol masers occur at frequencies of 6.7 GHz and 12.2 GHz, whereas Class I methanol masers occur at 44 GHz, 95 GHz, and 36 GHz.
Figure 1.3: Diagram showing the energy levels of type E methanol for different values of $K$, where $K$ is the projection of the total angular momentum $J$ onto the principal axes of the molecule. There are two species of methanol, E and A, differentiated by the spin orientations of their hydrogen atoms. This figure was derived from one due to Voronkov [2013] and used with the original authors permission.
Chapter 2

Data Sources

This thesis is based on observational data taken from the published literature. Since the data were obtained from several different sources that used a variety of telescopes with different setups, this chapter will discuss the sources used for the project and relevant observational parameters.

2.1 Data Collection

The primary motivation for this thesis was to find out what we could learn about high mass star formation based on the existing data on methanol masers. Since Class II methanol masers are generally found near protostars, and Class I methanol masers generally occur in outflows, we began by looking for high angular resolution data on Class I and Class II methanol masers in star forming regions; angular resolution is defined and discussed in the next paragraph. Val’tts & Larionov [2007] is a compiled catalog of all the known Class I methanol masers. From the 206 masers in their list, we picked the 44 GHz methanol masers that had been observed at high angular resolution with the the Karl G. Jansky Very Large Array (VLA, Figure 2.1); there were 32 sources of this kind. For each of these 32 maser sources, we searched the literature for Class II methanol masers within a 1′ radius of the position listed in the Val’tts & Larionov [2007] catalog. Since H$_2$O masers are also signposts of star formation, we searched the literature for H$_2$O masers near these Class I and II methanol masers. Recently, Cyganowski et al. [2011] have shown that 4.5 μm infrared sources are associated with high mass star formation, so we also looked for such sources near the Class I and II methanol masers. Finally, young high mass stars are known to form ultra compact (UC) ionized hydrogen (H II) regions by ionizing the hydrogen around them (Appendix A.5), so we also looked for data on UC H II regions.
Chapter 2. Data Sources

We wanted to work with the highest angular resolution data available for our sources. Therefore, we preferred to use data taken with interferometric telescopes like the VLA wherever available; a photograph of the VLA is shown in Figure 2.1. The angular (or spatial) resolution of a telescope is given by the ratio of the wavelength of observation to the diameter of the telescope. When signals from two radio telescope antennas are combined, the effective diameter of the telescope is the distance between the antennas. Therefore, by locating telescopes at large distances from each other as in the VLA, interferometers achieve much greater resolution than a single dish radio telescope. For example, the angular resolution of a single dish telescope of diameter 25 m would be about 60 arcseconds (written as $60''$) if it were observing at a frequency of 44 GHz. By way of comparison, Kurtz et al. [2004] were able to obtain a much higher angular resolution of $5''$, i.e., over ten times better, in their VLA observations of 44 GHz methanol masers discussed in § 2.2 below.

Figure 2.1: Photograph of the Karl G. Jansky Very Large Array. The individual antennas shown in the picture can be moved to larger distances along rail tracks to achieve even higher angular resolution.

2.2 Data Characteristics

We will now discuss the characteristics of the observed data, specifically, the papers we consulted, the telescope and observing parameters used to observe these data, and any other relevant information.

2.2.1 The Class I methanol maser data.

The positions of the 44 GHz Class I methanol masers were taken from the Val’tts & Larionov [2007] catalog. Most of the positions listed in this catalog were taken from VLA observations reported in Kurtz et al. [2004], from which we obtained information on the center velocities ($v_{\text{LSR}}$) and intensities of the methanol masers. Kurtz et al. [2004] was a survey of forty-four star forming regions in search of 44 GHz Class I methanol masers with the goal of investigating the relationship between such masers and shocked molecular gas. The angular resolution of this survey was about $0.5''$, and the velocity
resolution was 0.17 km s$^{-1}$ (corresponding to a frequency resolution of about 24 kHz). The idea of frequency resolution comes from the finite bandwidth of telescope receivers that must be sampled in discrete intervals. So, for example, Kurtz et al. [2004]’s survey used a frequency set up in which the bandwidth was 3.125 MHz sampled with 128 channels, to give a frequency resolution of 24 kHz. However, astronomers like to work with velocities because they can be connected more easily to the physical motions of the source(s) in the sky. For Galactic observations such as those studied in this thesis, one would convert from one to the other using the non relativistic Doppler effect: $\Delta v/c = \Delta f/f$, where $\Delta f$ is the shift in frequency from the observed frequency, $f$. The root mean square (rms) noise in the maser spectra line profiles, usually measured as one fifth of the peak-to-peak value in the line observed in a source-free region of the sky, was typically 40 mJy beam$^{-1}$, so they were able to detect masers down to a median 5-$\sigma$ limit of 0.2 Jy; intensity and flux and their units, Jy beam$^{-1}$ and Jy, are discussed in Appendix A.3. For several sources, Kurtz et al. [2004] found evidence for a spatial correlation between the 44 GHz masers and shocked molecular gas in agreement with the view that these masers are produced by collisional pumping in molecular outflows.

2.2.2 The Class II methanol maser data

The Class II methanol maser data were taken from a catalog of 6.7 GHz Class II methanol masers compiled by Pestalozzi et al. [2005]. This catalog contains 519 sources compiled from 62 references in the literature. Pestalozzi et al. [2005] found that Class II methanol masers trace the molecular ring of our galaxy where massive OB star associations (Appendix A.5) are found, in agreement with the idea that methanol masers are clearly associated with high mass star formation.

Pestalozzi et al. [2005] relied heavily on Caswell et al. [1995], which was a survey of thirty-six sites of 6.7 GHz methanol masers and forty sites of 1.7 GHz OH masers, conducted with the Australia Telescope Compact Array (ATCA). The purpose of this survey was to study the relationship between OH and CH$_3$OH masers and the evolution of massive stars. The angular resolution of the methanol maser observations was about 1.5", the frequency resolution was 0.97 kHz, and the rms noise was 60 mJy beam$^{-1}$.

For more recent data in the literature, we used Pandian et al. [2011] and Cyganowski et al. [2009]. Pandian et al. [2011] observed 57 Class II methanol masers at 6.7 GHz with the Multi-Element Radio-Linked Interferometer Network (MERLIN, Jodrell Bank) with an angular resolution of 60 milliarcseconds (mas), a frequency resolution of 3 kHz ($\equiv 0.13$ km s$^{-1}$), and an rms noise of about 35 mJy beam$^{-1}$. They found very close correspondence between methanol masers and 24 $\mu$m mid-infrared sources, lending further
support to theoretical models that predict methanol masers are pumped by infrared dust emission in the vicinity of high-mass protostars. Cyganowski et al. [2009] observed 44 GHz Class I and 6.7 GHz Class II methanol masers in 20 sources with the VLA. These twenty sources were selected based on 4.5 µm Spitzer infrared images (see § 2.2.5). The angular resolution of the 44 GHz VLA observations was 0.5′′-1′′, the frequency resolution was 24 kHz (≡ 0.17 km s$^{-1}$), and the rms noise was about 25 mJy beam$^{-1}$. The angular resolution of the 6.7 GHz VLA observations was 2′′ - 4′′, the frequency resolution was 3.05 kHz (≡0.14 km s$^{-1}$), and the rms noise was about 27 mJy beam$^{-1}$. Cyganowski et al. [2009] found a strong association between the 4.5 µm selected objects called EGOs (for “Extended Green Objects”) and Class II masers, and a widespread distribution of 44 GHz Class I masers in outflows, indicating that EGOs are young, high mass star forming objects that drive active outflows.

2.2.3 The H$_2$O maser data

Most of the H$_2$O maser data discussed in this thesis were taken from Hofner & Churchwell [1996] who obtained images and spectra for 21 H$_2$O maser sources in the vicinity of UC H II regions by observing with the VLA at 22 GHz. The angular resolution of their survey was 0.4′′, the frequency resolution was 24 kHz (≡ 3.5 km s$^{-1}$), and the typical RMS noise was 30 mJy beam$^{-1}$

2.2.4 The UC H II region data

Almost all of the UC H II region data in this thesis were taken from Wood & Churchwell [1989], who surveyed seventy-five UC H II regions with the VLA at frequencies of 4.9 GHz and 14.9 GHz. The goal of this survey was to understand the morphology and characteristics of the selected H II regions. The 14.9 GHz observations used for this thesis have an angular resolution of approximately 0.4′′ and an rms noise of about 0.32 mJy beam$^{-1}$. In addition, the data for one UC H II region in G45.47+0.07 were obtained from Urquhart et al. [2009], who observed 659 high mass star forming candidate regions with the VLA at 4.9 GHz in order to detect UC H II regions. The angular resolution of their observations was about 1.5′′, and the rms noise was about 0.2 mJy beam$^{-1}$. They identified 391 UC H II regions in this sample.

2.2.5 The 4.5 µm infrared data

The 4.5 µm infrared data used in this thesis were taken from the GLIMPSE catalog of the online Spitzer archive (where GLIMPSE stands for Galactic Legacy Infrared
Midplane Survey Extraordinaire). The GLIMPSE catalog (Churchwell et al. 2009) was compiled from observations taken with the Infrared Array Camera (IRAC) on board the Spitzer Space Telescope (Figure 2.2), which recorded data at wavelengths of 3.6 µm, 4.5 µm, 5.8 µm, and 8.0 µm. The angular resolution of GLIMPSE images is about 1.2″.

We use the 4.5 µm data because Cyganowski et al. [2008] have found that extended emission at 4.5 µm is associated with high mass star forming regions. This wavelength is usually colored green in most false color infrared images, hence the term extended “green” objects (EGO’s).
Figure 2.2: Figure showing a pre launch view of the Spitzer space telescope.
Chapter 3

Results

In this chapter, we present the results. In § 3.1, we discuss global features of our data. In § 3.2, we present a discussion of eight individual regions for which high resolution data were available for Class I and Class II methanol masers and associated tracers. In § 3.3, we present results for the regions for which high angular resolution data were available only for Class I and Class II methanol masers.

3.1 Masers and associated objects.

The data for this project were obtained by searching the literature for high angular resolution data on thirty star forming regions known to contain Class I and Class II methanol masers. In addition to these types of masers, we searched the literature for high angular resolution data on associated H$_2$O masers, ultra compact (UC) ionized hydrogen (H II) regions, and 4.5 µm Spitzer infrared images in these thirty star forming regions. As shown in Figure 3.1, all of these data were available for eight, or 27% of the thirty regions. For 13% of the regions, H$_2$O maser data, which were crucial to the analyses we intended to perform, were not found, while data on methanol masers, and UC H II regions were found. For the remaining 60% of the regions, high angular resolution data were present for the methanol masers only.
Chapter 3. Results

Figure 3.1: Pie chart showing the type and quality of available data. In addition to Class I and Class II methanol masers, we looked for data on H$_2$O masers, UC H II regions, and 4.5 µm infrared sources. All of these data were available for eight, or 27%, of the regions. For 13% of the regions, H$_2$O maser data were not found. For the remaining 60% of the regions, high resolution data were present for the methanol masers only.

3.2 Discussion of individual regions.

For those eight regions for which data are available in all the tracers listed in § 3.1, plots have been produced showing the positions of the Class I and II methanol masers, H$_2$O masers, UC H II regions and near infrared sources. Diagrams showing the center velocities ($v_{\text{LSR}}$) and intensities of the methanol and H$_2$O maser spectral lines were also produced for these regions.

With these plots of morphology and spectra we seek to address the following issues:

1. What is a typical range of projected distances between Class I and II methanol masers?

2. How do the center velocities ($v_{\text{LSR}}$) of the H$_2$O masers compare to that of the Class I and II methanol masers?

3. How are H$_2$O masers arranged in relation to these methanol masers? In particular, are there any arrangements that suggest a known configuration like an outflow or disk?
The eight regions will now be discussed individually.

### 3.2.1 Region G9.62+0.19

Figure 3.2 shows the Class II methanol maser and the Class I methanol maser in G9.62+0.19, together with other sources of interest. To the northwest of the Class I maser position is a Class II methanol maser, whose position is marked by a square in Figure 3.2. Following usual astronomical convention, east is to the left in Figure 3.2, and all other images in this thesis. The Class I and Class II masers are separated by about 10.7''; at a distance of 5.2 kiloparsec (kpc) to G9.62+0.19 (Sanna et al. 2009), this is equivalent to about 0.27 pc. The H$_2$O masers in this source are arranged along a narrow, almost linear, structure (Figure 3.2). There are three UC H II regions in this figure (Forster & Caswell 2000). There is a UC H II region about 3.4'' to the southwest of the Class I methanol maser, and a second UC H II region that is almost coincident with the Class II methanol maser. The grey scale shows the 4.5 \(\mu\)m infrared Spitzer image. About 3.8'' west of the Class I maser position lies a peak in this 4.5 \(\mu\)m image. The positions of these sources, together with the telescopes used to observe them and the angular resolution (in terms of synthesized beam) of the observations, are listed in Table 3.1.

The center velocities \(v_{\text{LSR}}\) and intensities of the Class I and Class II methanol masers and H$_2$O masers have been plotted in Figure 3.3. In this, and all other such figures, the \(v_{\text{LSR}}\) of the Class II methanol maser will be used as a reference; masers with \(v_{\text{LSR}}\) larger than the Class II methanol maser will be considered to be redshifted, and masers with \(v_{\text{LSR}}\) smaller than the Class II methanol maser will be considered to be blueshifted. Six of the eight H$_2$O masers in G9.62+0.19 are at larger center velocities \(v_{\text{LSR}}\) than the center velocity of the Class II methanol maser, that is, they are redshifted with respect to the Class II methanol maser. The Class I methanol maser is also redshifted (i.e., at larger \(v_{\text{LSR}}\)) with respect to the Class II methanol maser. A ninth H$_2$O maser with a center velocity of 25 km s$^{-1}$ is outside the range of the plot in Figure 3.3.
Figure 3.2: Figure showing the Class II and the Class I methanol maser and other sources of interest in region G9.62+0.19. The position of the Class I methanol maser is indicated by a diamond and the Class II methanol maser by a square. The open circles mark the positions of the $\text{H}_2\text{O}$ masers and the $\times$'s mark the peaks of the UC H II regions. In all cases, positional uncertainties are either equal to or smaller than the sizes of the markers themselves or are marked by a cross, if larger than the marker sizes. The grayscale shows the 4.5 $\mu$m Spitzer infrared image and the intensity range is between 1.61 MJy sr$^{-1}$ and 938 MJy sr$^{-1}$. Per usual astronomical convention for images, north is upward and east is to the left in this, and all other images in this thesis.
Figure 3.3: Plot of intensities and center velocities ($v_{\text{LSR}}$) of methanol and $\text{H}_2\text{O}$ masers associated with G9.62+0.19. At the top of each line is a symbol indicating the type of source; the Class I methanol maser is represented by a diamond, the Class II methanol maser by a triangle, and the $\text{H}_2\text{O}$ masers by filled circles. A $\text{H}_2\text{O}$ maser with a center velocity of 25 km s$^{-1}$ is outside the range of this plot. In this, and all other such figures, the $v_{\text{LSR}}$ of the Class II methanol maser will be used as a reference; masers with $v_{\text{LSR}}$ larger than the Class II methanol maser will be considered to be redshifted, and masers with $v_{\text{LSR}}$ smaller than the Class II methanol maser will be considered to be blueshifted.
Table 3.1: Positions and associated information for sources associated with G9.62+0.19

<table>
<thead>
<tr>
<th>Source Type</th>
<th>R.A. (J2000)</th>
<th>Dec. (J2000)</th>
<th>Observing Telescope</th>
<th>Synthesized Beam</th>
<th>$v_{\text{LSR}}$ (km s$^{-1}$)</th>
<th>Intensity (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>44 GHz Class I CH$_3$OH maser $^1$</td>
<td>18 06 15.1</td>
<td>-20 31 40</td>
<td>VLA $^2$</td>
<td>1.1&quot; × 1.1&quot;</td>
<td>3.7</td>
<td>2.1</td>
</tr>
<tr>
<td>12.2 GHz Class II CH$_3$OH maser $^3$</td>
<td>18 06 14.7</td>
<td>-20 31 32</td>
<td>VLBA $^4$</td>
<td>0.001&quot; × 0.001&quot;</td>
<td>1.3</td>
<td>5500</td>
</tr>
<tr>
<td>22 MHz H$_2$O maser $^5$</td>
<td>18 06 14.7</td>
<td>-20 31 31</td>
<td>VLA</td>
<td>0.64&quot; × 0.33&quot;</td>
<td>0.10</td>
<td>1.3</td>
</tr>
<tr>
<td>22 MHz H$_2$O maser</td>
<td>18 06 14.8</td>
<td>-20 31 34</td>
<td>VLA</td>
<td>0.64&quot; × 0.33&quot;</td>
<td>-9.8</td>
<td>2.9</td>
</tr>
<tr>
<td>22 MHz H$_2$O maser</td>
<td>18 06 14.8</td>
<td>-20 31 37</td>
<td>VLA</td>
<td>0.64&quot; × 0.33&quot;</td>
<td>5.3</td>
<td>17</td>
</tr>
<tr>
<td>22 MHz H$_2$O maser</td>
<td>18 06 14.9</td>
<td>-20 31 37</td>
<td>VLA</td>
<td>0.64&quot; × 0.33&quot;</td>
<td>6.0</td>
<td>2.2</td>
</tr>
<tr>
<td>22 MHz H$_2$O maser</td>
<td>18 06 14.9</td>
<td>-20 31 38</td>
<td>VLA</td>
<td>0.64&quot; × 0.33&quot;</td>
<td>7.3</td>
<td>1.5</td>
</tr>
<tr>
<td>22 MHz H$_2$O maser</td>
<td>18 06 14.9</td>
<td>-20 31 40</td>
<td>VLA</td>
<td>0.64&quot; × 0.33&quot;</td>
<td>7.0</td>
<td>6.4</td>
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<td>22 MHz H$_2$O maser</td>
<td>18 06 14.9</td>
<td>-20 31 41</td>
<td>VLA</td>
<td>0.64&quot; × 0.33&quot;</td>
<td>5.0</td>
<td>75</td>
</tr>
<tr>
<td>22 MHz H$_2$O maser</td>
<td>18 06 14.9</td>
<td>-20 31 41</td>
<td>VLA</td>
<td>0.64&quot; × 0.33&quot;</td>
<td>6.0</td>
<td>9.5</td>
</tr>
<tr>
<td>22 MHz H$_2$O maser</td>
<td>18 06 15.0</td>
<td>-20 31 42</td>
<td>VLA</td>
<td>0.64&quot; × 0.33&quot;</td>
<td>25</td>
<td>0.30</td>
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### Table 3.1: continued.

<table>
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<tr>
<th>Source Type</th>
<th>R.A. (J2000)</th>
<th>Dec. (J2000)</th>
<th>Observing Telescope</th>
<th>Synthesized Beam</th>
<th>$v_{\text{LSR}}$ (km s$^{-1}$)</th>
<th>Intensity (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.2 GHz and 9.2 GHz UCHII region</td>
<td>18 06 14.7</td>
<td>$-20 31 32$</td>
<td>ATCA $^7$</td>
<td>$1.1'' \times 1.2''$</td>
<td>-9</td>
<td>-9</td>
</tr>
<tr>
<td>8.2 GHz and 9.2 GHz UCHII region</td>
<td>18 06 14.4</td>
<td>$-20 31 26$</td>
<td>ATCA</td>
<td>$2.2'' \times 1.6''$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8.2 GHz and 9.2 GHz UCHII region</td>
<td>18 06 14.9</td>
<td>$-20 31 43$</td>
<td>ATCA</td>
<td>$0.7'' \times 0.6''$</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

$^1$All 44GHz class I methanol masers in this section were found in Val’tts & Larionov [2007] and Kurtz et al. [2004]  
$^2$The Karl G. Jansky Very Large Array.  
$^3$Minier et al. [2001]  
$^4$The Very Long Baseline Array.  
$^5$Information on all water masers taken from Hofner & Churchwell [1996] unless otherwise noted.  
$^6$All of these WC H II regions were reported in Forster & Caswell [2000]. Forster & Caswell [2000] explain that their observations were taken at both 8.2 and 9.2 GHz.  
$^7$The Australia Telescope Compact Array (ATCA).  
$^8$Sources consulted for data presented in this table reported different significant figures. For convenience the data have been rounded to the least number of significant figures. Information on the resolution of each observing instrument is presented in the column ‘synthesized beam’ which differs between instruments and configurations of the same instrument.  
$^9$UCH II regions are continuum data and, therefore, produce no line profile information.
3.2.2 Region G10.47+0.27

Figure 3.4 shows the Class II methanol maser and the Class I methanol maser in G10.47+0.27, together with other sources of interest. The Class II methanol maser is located to the southeast of the Class I maser position, and its position is marked by a square in Figure 3.4. The Class I and Class II masers are separated by about 15.3″; at a distance of 6.0 kpc to G10.47+0.27 (Pestalozzi et al. 2005), this is equivalent to about 0.44 pc. Two of the H$_2$O masers in this source are almost coincident with the Class II methanol maser, and a third is right next to it. There are three UC H II regions, two of which are almost coincident with the Class II methanol maser, and a third lies to the northeast of it. A line of strong 4.5 μm point sources lies to the east and southeast of the Class I methanol maser. The positions of these sources, together with the telescopes used to observe them and the angular resolution in terms of synthesized beam (see Appendix A.3) of the observations, are listed in Table 3.2.

The center velocities ($v_{\text{LSR}}$) and intensities of the Class I and Class II methanol masers and H$_2$O masers have been plotted in Figure 3.5. All the three H$_2$O masers shown in this figure are at smaller $v_{\text{LSR}}$ (i.e., blueshifted) than the Class II methanol maser. The Class I methanol maser is also blueshifted with respect to the Class II methanol maser.
Figure 3.4: Figure showing the Class II and the Class I methanol maser and other sources of interest in region G10.47+0.27. The symbols are the same as in Figure 3.2, and are also marked in a box at the top left of the figure. The grayscale shows the 4.5 $\mu$m Spitzer infrared image and the intensity range is between 2.22 MJy sr$^{-1}$ and 1100 MJy sr$^{-1}$. 
Figure 3.5: Plot of intensities and center velocities ($v_{\text{LSR}}$) of methanol and H$_2$O masers associated with G10.47+0.27. The symbols are the same as in Figure 3.3.
### Table 3.2: Positions and associated information for sources associated with G10.47+0.27

<table>
<thead>
<tr>
<th>Source Type</th>
<th>R.A. (J2000)</th>
<th>Dec. (J2000)</th>
<th>Observing Telescope</th>
<th>Synthesized Beam</th>
<th>$v_{\text{LSR}}$ (km s$^{-1}$)</th>
<th>Intensity (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>44 GHz Class I CH$_3$OH maser$^1$</td>
<td>18 08 37.4</td>
<td>-19 51 40</td>
<td>VLA</td>
<td>3.14&quot; × 1.33&quot;</td>
<td>67</td>
<td>1.9</td>
</tr>
<tr>
<td>6.7 GHz Class II CH$_3$OH maser$^2$</td>
<td>18 08 38.2</td>
<td>-19 51 50</td>
<td>ATCA</td>
<td>1.5&quot; × 1.5&quot;</td>
<td>75</td>
<td>120</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser$^3$</td>
<td>18 08 38.2</td>
<td>-19 51 50</td>
<td>VLA</td>
<td>0.48&quot; × 0.45&quot;</td>
<td>64</td>
<td>200</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>18 08 38.2</td>
<td>-19 51 49</td>
<td>VLA</td>
<td>0.48&quot; × 0.45&quot;</td>
<td>63</td>
<td>14</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>18 08 38.2</td>
<td>-19 51 49</td>
<td>VLA</td>
<td>0.48&quot; × 0.45&quot;</td>
<td>70</td>
<td>28</td>
</tr>
<tr>
<td>14.9 GHz UCHII region$^4$</td>
<td>18 08 38.2</td>
<td>-19 51 50</td>
<td>VLA</td>
<td>0.89&quot; × 0.57&quot;</td>
<td>.6</td>
<td>.6</td>
</tr>
<tr>
<td>14.9 GHz UCHII region</td>
<td>18 08 38.2</td>
<td>-19 51 49</td>
<td>VLA</td>
<td>0.79&quot; × 0.56&quot;</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>14.9 GHz UCHII region</td>
<td>18 08 38.3</td>
<td>-19 51 45</td>
<td>VLA</td>
<td>1.04&quot; × 0.79&quot;</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

$^1$Kurtz et al. [2004]  
$^2$Caswell et al. [1995]  
$^3$Hofner & Churchwell [1996]  
$^4$Wood & Churchwell [1989]  
$^5$Sources consulted for data presented in this table reported different significant figures. For convenience the data have been rounded to the least number of significant figures. Information on the resolution of each observing instrument is presented in the column ‘synthesized beam’ which differs between instruments and configurations of the same instrument.  
$^6$UCHII regions are continuum data and, therefore, produce no line profile information.
3.2.3 Region G12.20-0.11

Figure 3.6 shows the Class II methanol maser and the Class I methanol maser in G12.20-0.11, together with other sources of interest. The Class I and Class II masers are separated by about 32.4″; at a distance of 8.3 kpc to G12.20-0.11 (Pestalozzi et al. 2005), this is equivalent to about 1.3 pc. Six of the H$_2$O masers in this source are clustered around the Class I methanol maser. An ultracompact HII region (Appendix A.5) is to the south of the Class I methanol maser. To the east of the Class I methanol maser there is a strong 4.5 μm infrared source. Figure 3.7 shows the line velocities of the masers in this region. The positions of these sources, together with the telescopes used to observe them and the angular resolution (in terms of synthesized beam) of the observations, are listed in Table 3.3.

The center velocities ($v_{\text{LSR}}$) and intensities of the Class I and Class II methanol masers and H$_2$O masers have been plotted in Figure 3.7. Four of the eight H$_2$O masers are at $v_{\text{LSR}}$ greater than (i.e., redshifted) the $v_{\text{LSR}}$ of the Class II methanol maser. The Class I methanol maser is also redshifted with respect to the Class II methanol maser.

![Figure 3.6: Figure showing the Class II and the Class I methanol maser and other sources of interest in region G12.20-0.11. The grayscale shows the 4.5 μm Spitzer infrared image and the intensity range is between 2.58 MJy sr$^{-1}$ and 1220 MJy sr$^{-1}$. The symbols are the same as in Figure 3.2, and are also marked in a box at the top right of the figure.](image-url)
Figure 3.7: Plot of intensities and center velocities ($v_{LSR}$) of methanol and H$_2$O masers associated with G12.20-0.11. The symbols are the same as in Figure 3.3. For better visibility, an enlarged version of the 0-16 Jy segment in the upper plot is presented in the lower plot.
## Table 3.3: Positions and associated information for sources associated with G12.20-0.11

<table>
<thead>
<tr>
<th>Source Type</th>
<th>R.A. (J2000) (h m s)</th>
<th>Dec. (J2000) (° ' ″)</th>
<th>Observing Telescope</th>
<th>Synthesized Beam</th>
<th>$v_{\text{LSR}}$ (km s$^{-1}$)</th>
<th>Intensity (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>44 GHz Class I CH$_3$OH maser $^1$</td>
<td>18 12 39.9</td>
<td>-18 24 15</td>
<td>VLA</td>
<td>2.93″ × 1.43″</td>
<td>24</td>
<td>4.3</td>
</tr>
<tr>
<td>6.7 GHz Class II CH$_3$OH maser $^2$</td>
<td>18 12 40.1</td>
<td>-18 24 47</td>
<td>ATCA</td>
<td>1.5″ × 1.5″</td>
<td>20</td>
<td>15</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser $^3$</td>
<td>18 12 39.8</td>
<td>-18 24 17</td>
<td>VLA</td>
<td>0.49″ × 0.38″</td>
<td>-4.5</td>
<td>110</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>18 12 44.5</td>
<td>-18 24 25</td>
<td>VLA</td>
<td>0.49″ × 0.38″</td>
<td>26</td>
<td>70</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>18 12 39.8</td>
<td>-18 24 18</td>
<td>VLA</td>
<td>0.49″ × 0.38″</td>
<td>23</td>
<td>3.2</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>18 12 39.8</td>
<td>-18 24 16</td>
<td>VLA</td>
<td>0.49″ × 0.38″</td>
<td>32</td>
<td>1.5</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>18 12 44.5</td>
<td>-18 24 24</td>
<td>VLA</td>
<td>0.49″ × 0.38″</td>
<td>28</td>
<td>2.3</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>18 12 39.9</td>
<td>-18 24 26</td>
<td>VLA</td>
<td>0.49″ × 0.38″</td>
<td>8.0</td>
<td>0.50</td>
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<tr>
<td>22 GHz H$_2$O maser</td>
<td>18 12 40.1</td>
<td>-18 24 26</td>
<td>VLA</td>
<td>0.49″ × 0.38″</td>
<td>-18</td>
<td>0.40</td>
</tr>
<tr>
<td>14.9 GHz UCHII region $^4$</td>
<td>18 12 38.1</td>
<td>-18 25 10</td>
<td>VLA</td>
<td>0.4″ × 0.4″</td>
<td>-6</td>
<td>-</td>
</tr>
<tr>
<td>14.9 GHz UCHII region</td>
<td>18 12 43.7</td>
<td>-18 25 44</td>
<td>VLA</td>
<td>0.4″ × 0.4″</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>14.9 GHz UCHII region</td>
<td>18 12 39.9</td>
<td>-18 24 26</td>
<td>VLA</td>
<td>0.4″ × 0.4″</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

$^1$Kurtz et al. [2004]
$^2$Caswell et al. [1995]
$^3$Hofner & Churchwell [1996]
$^4$Wood & Churchwell [1989]
$^5$Sources consulted for data presented in this table reported different significant figures. For convenience the data have been rounded to the least number of significant figures. Information on the resolution of each observing instrument is presented in the column ‘synthesized beam’ which differs between instruments and configurations of the same instrument.
$^6$UCHII regions are continuum data and, therefore, produce no line profile information.
3.2.4 Region G31.41+0.31

Figure 3.8 shows the Class II methanol maser and the Class I methanol maser in G31.41+0.31, together with other sources of interest. The Class I methanol maser lies about 20.43" to the southeast of the Class I methanol maser; at a distance of 7.3 kpc to G31.41+0.31 (Pestalozzi et al. 2005), this is equivalent to about 0.72 pc. A complex of H$_2$O masers is about 5" north of the Class I methanol maser position. A UC HII region is 7" to the northeast of the Class I methanol maser. This region shows two weak 4.5 μm infrared sources, one about 10" north of the Class I methanol maser and the other to the west of the Class II methanol maser. The positions of these sources, together with the telescopes used to observe them and the angular resolution (in terms of synthesized beam) of the observations, are listed in Table 3.4.

The center velocities ($v_{\text{LSR}}$) and intensities of the Class I and Class II methanol masers and H$_2$O masers have been plotted in Figure 3.9. Six of the eight H$_2$O masers shown in this figure are at lower $v_{\text{LSR}}$ (i.e., blueshifted) than the Class II methanol maser. The Class I methanol maser is also blueshifted with respect to the Class II methanol maser.
Figure 3.9: Plot of intensities and center velocities ($v_{\text{LSR}}$) of methanol and H$_2$O masers associated with G31.41+0.31. The symbols are the same as in Figure 3.3. The lower plot is an enlarged version of the 0-15 Jy segment in the upper plot.
### Table 3.4: Positions and associated information for sources associated with G31.41+0.31

<table>
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<tr>
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<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>44 GHz Class I CH$_3$OH maser $^1$</td>
<td>18 47 34.2</td>
<td>-01 12 50</td>
<td>VLA</td>
<td>2.21&quot; × 1.36&quot;</td>
<td>100</td>
</tr>
<tr>
<td>6.7 GHz Class II CH$_3$OH maser $^2$</td>
<td>18 47 33.1</td>
<td>-01 12 38</td>
<td>ATCA</td>
<td>1.5&quot; × 1.5&quot;</td>
<td>104</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser $^3$</td>
<td>18 47 34.3</td>
<td>-01 12 45</td>
<td>VLA</td>
<td>0.47&quot; × 0.47&quot;</td>
<td>104</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>18 47 34.3</td>
<td>-01 12 46</td>
<td>VLA</td>
<td>0.47&quot; × 0.47&quot;</td>
<td>103</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>18 47 34.3</td>
<td>-01 12 46</td>
<td>VLA</td>
<td>0.47&quot; × 0.47&quot;</td>
<td>95.3</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>18 47 34.3</td>
<td>-01 12 46</td>
<td>VLA</td>
<td>0.47&quot; × 0.47&quot;</td>
<td>96.3</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>18 47 34.4</td>
<td>-01 12 44</td>
<td>VLA</td>
<td>0.47&quot; × 0.47&quot;</td>
<td>117</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>18 47 34.4</td>
<td>-01 12 45</td>
<td>VLA</td>
<td>0.47&quot; × 0.47&quot;</td>
<td>99.3</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>18 47 34.4</td>
<td>-01 12 46</td>
<td>VLA</td>
<td>0.47&quot; × 0.47&quot;</td>
<td>97.6</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>18 47 34.4</td>
<td>-01 12 48</td>
<td>VLA</td>
<td>0.47&quot; × 0.47&quot;</td>
<td>124</td>
</tr>
<tr>
<td>14.9 GHz UCHII region $^4$</td>
<td>18 47 34.6</td>
<td>-01 12 43</td>
<td>VLA</td>
<td>1.1&quot; × 1.1&quot;</td>
<td>-$^6$</td>
</tr>
</tbody>
</table>

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$^1$ Kurtz et al. [2004]  
$^2$ Caswell et al. [1995]  
$^3$ Hofner & Churchwell [1996]  
$^4$ Wood & Churchwell [1989]  
$^5$ Sources consulted for data presented in this table reported different significant figures. For convenience the data have been rounded to the least number of significant figures. Information on the resolution of each observing instrument is presented in the column ‘synthesized beam’ which differs between instruments and configurations of the same instrument.  
$^6$ UC HII regions are continuum data and, therefore, produce no line profile information.
3.2.5 Region G35.03+0.35

Figure 3.10 shows the Class II methanol maser and the Class I methanol maser in G35.03+0.35, together with other sources of interest. The Class I methanol maser lies almost due west of the Class II methanol maser by about 11.98″; at a distance of 6.9 kpc to G35.03+0.35 (Pestalozzi et al. 2005), this is equivalent to about 0.40 pc. There is only one H$_2$O maser in this source, and it lies to the west of the Class I methanol maser. Extended 4.5 μm emission straddles the region between the Class I methanol and H$_2$O maser. The positions of these sources, together with the telescopes used to observe them and the angular resolution (in terms of synthesized beam) of the observations, are listed in Table 3.5.

The center velocities ($v_{\text{LSR}}$) and intensities of the Class I and Class II methanol masers and H$_2$O masers have been plotted in Figure 3.11. The H$_2$O maser is at a higher $v_{\text{LSR}}$ (i.e., redshifted) than the Class II methanol maser. The Class I methanol maser is also redshifted with respect to the Class II methanol maser.

![Figure 3.10](image-url)  
**Figure 3.10:** Figure showing the Class II and the Class I methanol maser and other sources of interest in region G35.03+0.35. The grayscale shows the 4.5 μm Spitzer infrared image and the intensity range is between 0.374 MJy sr$^{-1}$ and 455 MJy sr$^{-1}$. The symbols are the same as in Figure 3.2.
Figure 3.11: Plot of intensities and center velocities ($v_{\text{LSR}}$) of methanol and H$_2$O masers associated with G35.03+0.35. The symbols are the same as in Figure 3.3. The lower plot is an enlarged version of the 0-0.7 Jy segment in the upper plot.
Table 3.5: Positions and associated information for sources associated with G35.03+0.35

<table>
<thead>
<tr>
<th>Source Type</th>
<th>R.A. (J2000)</th>
<th>Dec. (J2000)</th>
<th>Observing</th>
<th>Synthesized Beam</th>
<th>$v_{\text{LSR}}$ (km s$^{-1}$)</th>
<th>Intensity (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>44 GHz Class I CH$_3$OH maser $^1$</td>
<td>18 54 1.0</td>
<td>+02 01 20</td>
<td>VLA</td>
<td>0.58'' × 0.46''</td>
<td>56</td>
<td>0.67</td>
</tr>
<tr>
<td>6.7 GHz Class II CH$_3$OH maser $^2$</td>
<td>18 54 1.8</td>
<td>+02 01 19</td>
<td>VLA</td>
<td>2.32'' × 1.34''</td>
<td>44</td>
<td>21</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser $^3$</td>
<td>18 54 0.66</td>
<td>+02 01 19</td>
<td>VLA</td>
<td>2.6'' × 1.8''</td>
<td>68</td>
<td>19</td>
</tr>
<tr>
<td>14.9 GHz UCHII region $^4$</td>
<td>18 51 29</td>
<td>+01 57 31</td>
<td>VLA</td>
<td>0.93'' × 0.8''</td>
<td>$^6$</td>
<td>$^6$</td>
</tr>
</tbody>
</table>

$^1$Kurtz et al. [2004]
$^2$Caswell et al. [1995]
$^3$Hofner & Churchwell [1996]
$^4$Wood & Churchwell [1989]

$^5$Sources consulted for data presented in this table reported different significant figures. For convenience the data have been rounded to the least number of significant figures. Information on the resolution of each observing instrument is presented in the column ‘synthesized beam’ which differs between instruments and configurations of the same instrument.

$^6$UC HII regions are continuum data and, therefore, produce no line profile information.
3.2.6 Region G45.07+0.13

Figure 3.12 shows the Class II methanol maser and the Class I methanol maser in G45.07+0.13, together with other sources of interest. To the south of the Class I maser position is a Class II methanol maser, whose position is marked by a square in Figure 3.12. The Class I and Class II masers are separated by about 5.96″; at a distance of 6.0 kpc to G45.07+0.13 (Pestalozzi et al. 2005), this is equivalent to about 0.17 pc. A UC HII region is almost coincident with the Class II methanol maser position, and there is 4.5 µm emission in the entire region. The positions of these sources, together with the telescopes used to observe them and the angular resolution (in terms of synthesized beam) of the observations, are listed in Table 3.6.

The center velocities (v<sub>LSR</sub>) and intensities of the Class I and Class II methanol masers and H<sub>2</sub>O masers have been plotted in Figure 3.13. Four of the five H<sub>2</sub>O masers shown in this figure are at larger v<sub>LSR</sub> (i.e., redshifted) than the Class II methanol maser. The Class I methanol maser is also redshifted with respect to the Class II methanol maser.

Figure 3.12: Figure showing the Class II and the Class I methanol maser and other sources of interest in region G45.07+0.13. The grayscale shows the 4.5 µm Spitzer infrared image and the intensity range is between 0.0683 MJy sr<sup>−1</sup> and 543 MJy sr<sup>−1</sup>. The symbols are the same as in Figure 3.2.
Figure 3.13: Plot of intensities and center velocities ($v_{\text{LSR}}$) of methanol and H$_2$O masers associated with G45.07+0.13. The symbols are the same as in Figure 3.3. The lower plot is an enlarged version of the 0-3 Jy segment in the upper plot.
<table>
<thead>
<tr>
<th>Source Type</th>
<th>R.A. (J2000)</th>
<th>Dec. (J2000)</th>
<th>Observing Telescope</th>
<th>Synthesized Beam</th>
<th>$v_{\text{LSR}}$ (km s$^{-1}$)</th>
<th>Intensity (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>44 GHz Class I CH$_3$OH maser</td>
<td>19 13 22.1</td>
<td>+10 50 59</td>
<td>VLA</td>
<td>1.98\arcsec $\times$ 1.6\arcsec</td>
<td>59.3</td>
<td>1.1</td>
</tr>
<tr>
<td>6.7 GHz Class II CH$_3$OH maser</td>
<td>19 13 22.1</td>
<td>+10 50 53</td>
<td>MERLIN$^5$</td>
<td>0.4\arcsec $\times$ 0.4\arcsec</td>
<td>57.8</td>
<td>64</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser $^3$</td>
<td>19 13 22.1</td>
<td>+10 50 53</td>
<td>VLA</td>
<td>0.61\arcsec $\times$ 0.37\arcsec</td>
<td>60.7</td>
<td>11</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>19 13 22.1</td>
<td>+10 50 53</td>
<td>VLA</td>
<td>2.6\arcsec $\times$ 0.37\arcsec</td>
<td>63.3</td>
<td>45</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>19 13 22.1</td>
<td>+10 50 56</td>
<td>VLA</td>
<td>0.4\arcsec $\times$ 0.37\arcsec</td>
<td>60.6</td>
<td>22</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>19 13 22.1</td>
<td>+10 50 56</td>
<td>VLA</td>
<td>0.4\arcsec $\times$ 0.37\arcsec</td>
<td>64.3</td>
<td>38</td>
</tr>
<tr>
<td>14.9 GHz UCHII region $^4$</td>
<td>19 13 23.7</td>
<td>+10 50 52</td>
<td>VLA</td>
<td>0.80\arcsec $\times$ 0.72\arcsec</td>
<td>.7</td>
<td>.7</td>
</tr>
</tbody>
</table>

$^1$Kurtz et al. [2004]  
$^2$Caswell et al. [1995]  
$^3$Hofner & Churchwell [1996]  
$^4$Wood & Churchwell [1989]  
$^5$Multi-Element Radio Linked Interferometer Network (MERLIN)  
$^6$Sources consulted for data presented in this table reported different significant figures. For convenience the data have been rounded to the least number of significant figures. Information on the resolution of each observing instrument is presented in the column ‘synthesized beam’ which differs between instruments and configurations of the same instrument.  
$^7$UCHII regions are continuum data and, therefore, produce no line profile information.
3.2.7 Region G45.47+0.07

Figure 3.14 shows the Class II methanol maser and the Class I methanol maser in G45.47+0.07, together with other sources of interest. The Class I and Class II masers are separated by about 115.2\arcsec; at a distance of 4.0 kpc to G45.47+0.07 (Pestalozzi et al. 2005), this is equivalent to about 2.23 pc. A UC HII region is 12\arcsec due south of the Class I methanol maser position. The 4.5 \mu m infrared emission is present throughout the region, with discrete enhancements at several locations, including one that is almost coincident with the position of the UC HII region. The positions of these sources, together with the telescopes used to observe them and the angular resolution (in terms of synthesized beam) of the observations, are listed in Table 3.7.

The center velocities ($v_{\text{LSR}}$) and intensities of the Class I and Class II methanol masers and H$_2$O masers have been plotted in Figure 3.15. Both of the H$_2$O masers are at larger $v_{\text{LSR}}$ (i.e., redshifted) than the Class II methanol maser. The Class I methanol maser is also redshifted with respect to the the Class II methanol maser.

![Figure 3.14: Figure showing the Class II and the Class I methanol maser and other sources of interest in region G45.47+0.07. The grayscale shows the 4.5 \mu m Spitzer infrared image and the intensity range is between 0.385 MJy sr$^{-1}$ and 538 MJy sr$^{-1}$. The symbols are the same as in Figure 3.2.](image-url)
Figure 3.15: Plot of intensities and center velocities ($v_{\text{LSR}}$) of methanol and H$_2$O masers associated with G45.47+0.07. The symbols are the same as in Figure 3.3.
Table 3.7: Positions and associated information for sources associated with G45.47+0.07

<table>
<thead>
<tr>
<th>Source Type</th>
<th>R.A. (J2000)</th>
<th>Dec. (J2000)</th>
<th>Observing</th>
<th>Synthesized Beam</th>
<th>$v_{\text{LSR}}$ (km s$^{-1}$)</th>
<th>Intensity (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>44 GHz Class I CH$_3$OH maser$^1$</td>
<td>$19^h14^m25.7^s$</td>
<td>+11 09 37</td>
<td>VLA</td>
<td>$2.17'' \times 1.54''$</td>
<td>65</td>
<td>0.55</td>
</tr>
<tr>
<td>6.7 GHz Class II CH$_3$OH maser$^2$</td>
<td>$19^h14^m18.3^s$</td>
<td>+11 08 59</td>
<td>MERLIN$^6$</td>
<td>$0.1'' \times 0.1''$</td>
<td>50</td>
<td>0.68</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser$^3$</td>
<td>$19^h14^m18.1^s$</td>
<td>+11 08 47</td>
<td>VLA</td>
<td>$2.6'' \times 1.8''$</td>
<td>61</td>
<td>4.4</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>$19^h14^m25.7^s$</td>
<td>+11 09 30</td>
<td>VLA</td>
<td>$3.5'' \times 1.1''$</td>
<td>69</td>
<td>1.3</td>
</tr>
<tr>
<td>5 GHz UCHII region$^4$</td>
<td>$19^h14^m25.7^s$</td>
<td>+11 09 26</td>
<td>VLA</td>
<td>$0.42'' \times 0.42''$</td>
<td>$.8$</td>
<td>$.8$</td>
</tr>
<tr>
<td>14.9 GHz UCHII region$^5$</td>
<td>$19^h14^m19.6^s$</td>
<td>+11 10 35</td>
<td>VLA</td>
<td>$0.4'' \times 0.4''$</td>
<td>$.8$</td>
<td>$.8$</td>
</tr>
</tbody>
</table>

$^1$Kurtz et al. [2004]
$^2$Pandian et al. [2011]
$^3$Hofner & Churchwell [1996]
$^4$Urquhart et al. [2009]
$^5$Wood & Churchwell [1989]
$^6$Multi-Element Radio Linked Interferometer Network (MERLIN)
$^7$Sources consulted for data presented in this table reported different significant figures. For convenience the data have been rounded to the least number of significant figures. Information on the resolution of each observing instrument is presented in the column 'synthesized beam' which differs between instruments and configurations of the same instrument.
$^8$UCHII regions are continuum data and, therefore, produce no line profile information.
3.2.8 Region G75.78+0.34

Figure 3.16 shows the Class II methanol maser and the Class I methanol maser in G45.47+0.07, together with other sources of interest. The Class I and Class II masers are separated by about 7.12″; at a distance of 4.9 kpc to G75.78+0.34 (Pestalozzi et al. 2005), this is equivalent to about 0.17 pc. Two H$_2$O masers lie 10.0″ to the southwest of the Class I methanol maser. The positions of these sources, together with the telescopes used to observe them and the angular resolution (in terms of synthesized beam) of the observations, are listed in Table 3.8.

The center velocities ($v_{\text{LSR}}$) and intensities of the Class I and Class II methanol masers and H$_2$O masers have been plotted in Figure 3.17. Two of the three H$_2$O masers are at smaller $v_{\text{LSR}}$ (i.e., blueshifted) than the Class II methanol maser. The Class I methanol maser is also blueshifted with respect to the Class II methanol maser.
Figure 3.17: Plot of intensities and center velocities ($v_{\text{LSR}}$) of methanol and H$_2$O masers associated with G75.78+0.34. The symbols are the same as in Figure 3.3.
Table 3.8: Positions and associated information for sources associated with G75.78+0.34

<table>
<thead>
<tr>
<th>Source Type</th>
<th>R.A. (J2000)</th>
<th>Dec. (J2000)</th>
<th>Observing</th>
<th>Synthesized Beam</th>
<th>$v_{\text{LSR}}$ (km s$^{-1}$)</th>
<th>Intensity (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>44 GHz Class I CH$_3$OH maser</td>
<td>20 21 44.4</td>
<td>+37 26 48</td>
<td>VLA</td>
<td>1.5″ × 1.5″</td>
<td>3.8</td>
<td>8.7</td>
</tr>
<tr>
<td>6.7 GHz Class II CH$_3$OH maser</td>
<td>20 21 44.7</td>
<td>+37 26 42</td>
<td>VLA</td>
<td>0.5″ × 0.5″</td>
<td>-2.9</td>
<td>39</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>20 21 44.0</td>
<td>+37 26 38</td>
<td>VLA</td>
<td>0.52″ × 0.3″</td>
<td>2.6</td>
<td>58</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>20 21 44.0</td>
<td>+37 26 37</td>
<td>VLA</td>
<td>0.52″ × 0.3″</td>
<td>14</td>
<td>4.2</td>
</tr>
<tr>
<td>22 GHz H$_2$O maser</td>
<td>20 21 44.0</td>
<td>+37 26 37</td>
<td>VLA</td>
<td>0.52″ × 0.3″</td>
<td>2.3</td>
<td>40</td>
</tr>
</tbody>
</table>

1Kurtz et al. [2004]
2Caswell et al. [1995]
3Hofner & Churchwell [1996]
4Wood & Churchwell [1989]
5Sources consulted for data presented in this table reported different significant figures. For convenience the data have been rounded to the least number of significant figures. Information on the resolution of each observing instrument is presented in the column ‘synthesized beam’ which differs between instruments and configurations of the same instrument.


3.3 Regions for which high resolution data were only available for Class I and Class II methanol masers.

In Figure 3.1, we saw that for 60% of the regions we examined, high resolution data were present for the Class I and Class II methanol masers only, but not for the other associated tracers of star formation discussed in § 3.2. The data on these methanol masers for such regions are presented in Table 3.9, including coordinates of each region, the offset in pc between the Class I and Class II methanol masers, and the characteristics of the spectral lines of each maser.

The projected distance between Class I and Class II methanol masers in these twenty-two regions is in general agreement with the separation between masers discussed in § 3.2.1 to § 3.2.8. The maximum angular separation is $59.34''$ for G24.943$+0.074$; at a distance of 7.7 kpc (Pestalozzi et al. 2005), this works out to 2.2 pc, similar to the projected distance between Class I and Class II masers in G45.47$+0.07$. The minimum projected separation was zero in three cases: G28.28-0.36, G37.47-0.11, G49.27-0.34, but that is likely due to the resolution of the observations not being great enough to resolve the Class I and Class II methanol maser sources. The mean projected separation between Class I and Class II methanol masers for all thirty regions discussed in this thesis was 0.67 pc with a root mean squared error of 0.12 pc.
Table 3.9: Regions with high resolution data for methanol masers only

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(h m s)</td>
<td>($^\circ$ $\arcmin$ $\arcsec$)</td>
<td>(pc)</td>
<td>$v_{LSR}$ (km s$^{-1}$)</td>
<td>Intensity (Jy)</td>
</tr>
<tr>
<td>G13.66-0.60</td>
<td>18 17 22.9</td>
<td>-17 22 13.8</td>
<td>0.84±0.02</td>
<td>48</td>
<td>28</td>
</tr>
<tr>
<td>G19.36-0.02</td>
<td>18 26 25.8</td>
<td>-12 03 56.9</td>
<td>0.96±0.06</td>
<td>27</td>
<td>54</td>
</tr>
<tr>
<td>G43.04-0.45</td>
<td>19 11 38.8</td>
<td>08 46 37.9</td>
<td>0.67±0.01</td>
<td>58</td>
<td>3.8</td>
</tr>
<tr>
<td>G94.26-0.41</td>
<td>21 32 30.7</td>
<td>51 02 14.9</td>
<td>0.31±0.01</td>
<td>-48</td>
<td>1.1</td>
</tr>
<tr>
<td>G10.29-0.13</td>
<td>18 08 49.5</td>
<td>-20 05 53.5</td>
<td>0.35±0.01</td>
<td>14</td>
<td>2.0</td>
</tr>
<tr>
<td>G14.89-0.40</td>
<td>18 19 7.60</td>
<td>-16 11 25.6</td>
<td>0.61±0.01</td>
<td>62</td>
<td>7.8</td>
</tr>
<tr>
<td>G18.66+0.04</td>
<td>18 24 53.7</td>
<td>-12 39 20.0</td>
<td>1.6±0.02</td>
<td>80</td>
<td>2.1</td>
</tr>
<tr>
<td>G18.89-0.47</td>
<td>18 27 7.90</td>
<td>-12 41 35.5</td>
<td>0.01±0.01</td>
<td>66</td>
<td>2.0</td>
</tr>
<tr>
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<td>-09 34 47.0</td>
<td>0.97±0.02</td>
<td>51</td>
<td>32</td>
</tr>
<tr>
<td>G23.96-0.11</td>
<td>18 35 22.3</td>
<td>-08 01 28.0</td>
<td>0.72±0.02</td>
<td>73</td>
<td>6.2</td>
</tr>
<tr>
<td>G24.94+0.07</td>
<td>18 36 31.5</td>
<td>-07 04 16.0</td>
<td>2.2±0.02</td>
<td>41</td>
<td>1.7</td>
</tr>
<tr>
<td>G25.27-0.43</td>
<td>18 38 56.9</td>
<td>-07 00 48.0</td>
<td>0.03±0.01</td>
<td>60</td>
<td>6.2</td>
</tr>
<tr>
<td>G28.28-0.36</td>
<td>18 44 13.2</td>
<td>-04 18 4.00</td>
<td>0.00±0.02</td>
<td>48</td>
<td>4.1</td>
</tr>
<tr>
<td>G28.84-0.25</td>
<td>18 44 51.0</td>
<td>-03 45 49.0</td>
<td>1.1±0.02</td>
<td>87</td>
<td>5.6</td>
</tr>
<tr>
<td>G34.82+0.35</td>
<td>18 53 37.7</td>
<td>01 50 25.4</td>
<td>0.31±0.01</td>
<td>57</td>
<td>0.67</td>
</tr>
<tr>
<td>-----------------</td>
<td>--------------</td>
<td>--------------</td>
<td>----------------</td>
<td>-------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td></td>
<td>(h m s)</td>
<td>(° ′ ″)</td>
<td>(pc)</td>
<td>$v_{\text{LSR}}$ (km s$^{-1}$)</td>
<td>Intensity (Jy)</td>
</tr>
<tr>
<td>G36.11+0.55</td>
<td>18 55 16.8</td>
<td>03 05 6.70</td>
<td>1.0±0.01</td>
<td>76</td>
<td>0.57</td>
</tr>
<tr>
<td>G37.27+0.08</td>
<td>18 59 3.73</td>
<td>03 53 42.9</td>
<td>0.88±0.01</td>
<td>90</td>
<td>1.0</td>
</tr>
<tr>
<td>G37.47-0.11</td>
<td>19 00 7.00</td>
<td>03 59 53.0</td>
<td>0.00±0.01</td>
<td>59</td>
<td>0.31</td>
</tr>
<tr>
<td>G39.10+0.48</td>
<td>19 00 58.1</td>
<td>05 42 44.0</td>
<td>0.62±0.01</td>
<td>27</td>
<td>11</td>
</tr>
<tr>
<td>G49.27-0.34</td>
<td>19 23 6.70</td>
<td>14 20 13.0</td>
<td>0.00±0.01</td>
<td>67</td>
<td>0.65</td>
</tr>
</tbody>
</table>

1Kurtz et al. [2004]
2Cyganowski et al. [2009]
3Pestalozzi et al. [2005]
4Pestalozzi et al. [2005] reports a position fix only.
5Each source consulted for data presented in this table reported different significant figures. For a valid comparison the data has been rounded to the least number of significant figures.
6The values in this column were computed using a measurement of the distance from our sun to the region in question, the error indicates the propagated uncertainty in the determination of the heliocentric distance.
Chapter 4

Discussion

In this chapter, we discuss the morphology and kinematics of the eight regions for which high resolution data were available. In § 4.1, we identify three patterns of morphology and a notable trend in the center velocities of the masers. In § 4.2 we describe three physical models which can explain the patterns discussed in § 4.1.

4.1 Morphology and Kinematics

Of the thirty regions that we found to have data on Class I and Class II methanol masers, we were able to obtain high resolution data for associated star formation tracers for eight regions. Such associated data include H$_2$O masers, ultracompact (UC) ionized hydrogen (H II) regions, and 4.5 µm infrared data from Spitzer. For these eight regions, we looked at the morphology of Class I and II methanol masers, and H$_2$O masers, and the center velocities of the line profiles of these masers. We also looked at the location of the UC H II regions and 4.5 µm infrared sources. Based on our examination of these data, we have identified three distinct patterns in the morphology of the masers, and one notable trend in the center velocities of the Class I methanol and H$_2$O maser spectral lines in relation to the center velocity of the Class II methanol masers.

4.1.1 Linear arrangement of H$_2$O masers

In two of the eight sources, G9.62+0.19 and G45.07+0.13, the H$_2$O masers are in a linear arrangement, spread out along a straight line (approximately) between the Class I and Class II methanol maser (Figure 3.2 and 3.12). There are nine H$_2$O masers in G9.62+0.19, but only five in G45.07+0.13, so the linear structure is more pronounced in G9.62+0.19. The projected separation between the two classes of methanol maser
is 0.27 pc for G9.62+0.19 and 0.17 pc for G45.07+0.13. A UC H II region is almost coincident with the Class II methanol maser in both sources. Since UC H II regions are formed by hot and massive young protostars, it is reasonable to conclude that the same ionizing radiation that is producing the UC H II region is also likely providing the radiative excitation of the Class II methanol maser. The linear arrangement of H$_2$O masers between the Class II and Class I methanol masers in both G9.62+0.19 and G45.07+0.13 is also suggestive of an outflow, with the Class I methanol maser excited near the head of the outflow in both sources. As stated in § 3.2.1, we consider masers with $v_{\text{LSR}}$ larger than the $v_{\text{LSR}}$ of the Class II methanol maser to be redshifted. Seven of the nine H$_2$O masers in G9.62+0.19 are redshifted with respect to the Class II methanol maser (e.g., see Table 3.1, where the $v_{\text{LSR}}$ of 7 H$_2$O masers are larger than the $v_{\text{LSR}}$ of the Class II methanol maser, and Figure 3.3). Therefore, these 7 masers are likely in the redshifted lobe of the outflow (see § 4.2.1 for additional discussion). The Class I methanol maser also has a larger $v_{\text{LSR}}$ than the $v_{\text{LSR}}$ of the Class II maser, so it can also be located in the redshifted lobe of the outflow. Likewise, in G45.07+0.13, three out of four masers are redshifted with respect to the Class II methanol maser, as is the Class I methanol maser (Table 3.6 and Figure 3.13).

In G9.62+0.19, however, we cannot rule out that the Class I methanol maser may not be associated with the Class II methanol maser, particularly given the recent discovery by Voronkov et al. [2010] that suggests that Class I masers may also be excited in shocks driven by expanding H II regions. Indeed, there is a UC H II region to the southwest of the Class I methanol maser in G9.62+0.19 and a 4.5 $\mu$m infrared source near the UC H II region, indicating another center of high mass star formation activity at this location (Figure 3.2). Still, with 7 of 9 H$_2$O masers in G9.62+0.19 redshifted with respect to the Class II maser, the outflow interpretation is reasonable, so that the data are certainly compatible with disk-outflow systems.

4.1.2 H$_2$O masers clustered near Class II methanol maser

In two of the eight regions, G10.47+0.27 and G75.78+0.34, the H$_2$O masers are far away from the Class I methanol maser (Figure 3.4 and 3.16). In G10.47+0.27, all the three H$_2$O masers are near the Class II methanol maser. A faint 4.5 $\mu$m source and a UC H II region are coincident with the Class II and H$_2$O maser position. As stated in § 3.2.1, we consider masers with $v_{\text{LSR}}$ smaller than the $v_{\text{LSR}}$ of the Class II methanol maser to be blueshifted. All three H$_2$O masers in G10.47+0.27, and the Class I methanol maser, are blueshifted with respect to the Class II methanol maser (Table 3.2 and Figure 3.5).
Chapter 4. Discussion

In G75.78+0.34, all three H$_2$O masers are at $\sim$ 9.1 pc from the Class II methanol maser, but a line from the Class II methanol maser to the H$_2$O masers is roughly perpendicular to a line joining the Class I and II methanol masers (Figure 3.16). An extended 4.5 $\mu$m source straddles the Class II methanol maser and H$_2$O maser positions. All three H$_2$O masers, and the Class I methanol maser, are redshifted with respect to the Class II methanol maser (Table 3.8 and Figure 3.17). We speculate that the Class II methanol maser and H$_2$O masers are located in a circumstellar disk in both these sources, and discuss this further in § 4.2.2.

4.1.3 H$_2$O masers clustered near Class I methanol maser

In three of the eight sources, G12.20-0.11, G31.41+0.31, and G35.03+0.35, the H$_2$O masers are far away from the Class II methanol maser, but are located near the Class I methanol maser (Figures 3.6, 3.8, and 3.10). Of the 6 masers near the Class I methanol maser in G12.20-0.11, two H$_2$O masers, and the Class I methanol maser, are redshifted with respect to the Class II methanol maser (Table 3.3 and Figure 3.7). Meanwhile, three H$_2$O masers are blueshifted, and one has the same center velocity, as the Class II methanol maser. Of the 8 masers in G31.41+0.31, five H$_2$O masers, and the Class I methanol maser, are blueshifted with respect to the Class II methanol maser, whereas two H$_2$O masers are redshifted, and one has the same $v_{\text{LSR}}$ as the Class II methanol maser (Table 3.4 and Figure 3.9). There is only one H$_2$O maser in G35.03+0.35, and it, along with the Class I methanol maser, is redshifted with respect to the Class II water maser (Table 3.5 and Figure 3.11). In all the three regions, G12.20-0.11, G31.41+0.31, and G35.03+0.35, there is a 4.5 $\mu$m source that is closer to the Class I methanol maser than the Class II methanol maser. In § 4.2.3, we will ascribe the geometry in these sources to one or more outflows.

4.1.4 The eighth source G45.47+0.07

The eighth source for which we have high angular resolution data for H$_2$O masers and other associated tracers, G45.47+0.07, does not fit into any of the three categories listed above. It has one H$_2$O maser near the Class I methanol maser source, and one H$_2$O maser near the Class II methanol maser source (Figure 3.14). The Class I methanol maser, an H$_2$O maser near it, and the H$_2$O maser near the Class II methanol maser, are all redshifted with respect to the Class II methanol maser (Table 3.7 and Figures 3.15). We interpret this as a hybrid of the models discussed in § 4.1.2 and § 4.1.3, and discuss it further in § 4.2.4.
4.2 Models based on high angular resolution data.

Based on our findings (Chapter 3) and discussion in § 4.1, we have constructed three disk-outflow models for methanol masers in star forming regions. As discussed in Chapter 1, star formation is accompanied by a circumstellar disk from which the central protostar accretes material, and a bipolar outflow at right angles to the circumstellar disk which carries mass and angular momentum away from the protostar (Figure 4.1). In general, the disk may be inclined at some angle to the line of sight, in which case one lobe of the outflow would be redshifted and the other blueshifted. We will now discuss each model in detail.

![Diagram showing an accretion disk and outflow from a massive young protostar.](image)

**Figure 4.1:** Diagram showing an accretion disk and outflow from a massive young protostar. As discussed in Chapter 1, star formation is accompanied by a circumstellar disk from which the central protostar accretes material, and a bipolar outflow at right angles to the disk which carries mass and angular momentum away from the protostar. Using the same symbols as were used in Chapter 3 we have shown some typical locations for Class I and Class II methanol masers and water masers in relation to the circumstellar disk, outflow and massive protostar. In general, the disk may be inclined at some angle to the line of sight, in which case one lobe of the outflow would be redshifted and the other blueshifted.
4.2.1 Disk-outflow model 1

Our first model is based on the morphology of methanol and H$_2$O masers in G9.62+0.19 and G45.07+0.13 (§3.2.1, §3.2.6, and §4.1.1). Figure 4.2 shows the model of the disk and outflow, together with the locations of the Class II and Class I methanol masers, and the H$_2$O masers. We have chosen to put the information from the G9.62+0.19 star forming region (§3.2.1) in the figure. Since it is known that Class II methanol masers are usually found near protostars, we have put the disk near the Class II methanol maser source. Next, it is well known that H$_2$O masers are formed in both outflows and circumstellar disks in high mass star forming regions. Except for the two water masers nearest to the Class II methanol maser in G9.62+0.19, all the other 7 masers are redshifted (i.e., at higher center velocities, $v_{\text{LSR}}$) with respect to the Class II methanol maser, and well separated from it in position, as is the Class I methanol maser. Therefore, we interpret all of them to be part of the redshifted lobe of the outflow. We have used the position of the H$_2$O maser on the extreme right and the Class I methanol maser on the left in G9.62+0.19 to constrain the edges of the redshifted outflow lobe, giving us a nominal opening angle of 23° for the outflow. Choosing the edges of the two redshifted H$_2$O masers in G45.07+0.13 also gives us a similar opening angle for the outflow. In both regions, therefore, the outflow appears to be well collimated. This is usually the case in low mass star forming regions in the earlier stages of star formation, and has been known to be true in high mass star forming regions whenever outflows can be disentangled between sources (McKee & Ostriker 2007). In other words, due to the multiplicity of sources in high mass star forming regions, it is usually difficult to tell which outflow is coming from which source. Here, however, if all the redshifted masers are truly part of the same redshifted outflow lobe that is centered near the Class II methanol maser location, then the smaller value of the collimation angle that we have obtained is as expected. For example, in low mass star forming regions, Arce et al. [2007] described collimation angles of a few degrees, and in high mass star forming regions, Beuther et al. [2005] found outflows collimated to the same degree as in low mass star forming regions. The two blueshifted H$_2$O masers in Figure 4.2 near the Class II methanol maser in G9.62+0.19 may be part of the blueshifted lobe of the outflow or may be part of the circumstellar disk of the protostar. We favor the latter interpretation for the southeastern blue shifted maser, at least, since the blueshifted lobe should be opposite the redshifted lobe. Likewise the redshifted and blueshifted masers that are almost coincident with the Class II methanol maser in G45.07+0.13 (Figure 3.12 and Table 3.6) could be interpreted as being at the base of the redshifted and blueshifted outflow lobes, or they could be in the circumstellar disk around the protostar.

While the model of the disk and the redshifted lobe given above is one interpretation
of the data, it is worth noting that the morphology of methanol and H$_2$O masers in G9.62+0.19 in particular, does support other geometries that we have not considered here. For example, Voronkov et al. [2010] have suggested that some Class I methanol masers may be excited in shocks driven by expanding H II regions. We note that there is a UC H II region to the southwest of the Class I methanol maser in G9.62+0.19 (Figure 3.2) which could be responsible for the shock causing the Class I methanol maser.

### 4.2.2 Disk-outflow model 2

The second model is based on the morphology of methanol and H$_2$O masers in G10.47+0.27 and G75.78+0.34 (§ 3.2.2, § 3.2.8, and § 4.1.2). Figure 4.3 shows the model of the disk and outflow, together with the locations of the Class II and Class I methanol masers, and the H$_2$O masers. We have chosen to put the information from G10.47+0.27 (§ 3.2.2) into Figure 4.3. In both these sources, we interpret the H$_2$O masers to be located in a circumstellar disk together with the Class II methanol maser,
with the Class I methanol maser located in the outflow. This is a reasonable interpretation for G10.47+0.27, where the H$_2$O masers are clustered close to the Class II methanol maser (Figure 3.4). In G75.78+0.34, however, while the geometry suggests such an interpretation (Figure 3.16), the size of the circumstellar disk would be too large, if it were to be constrained by the distance between the H$_2$O masers and the Class II methanol maser, which is 0.2 pc $\equiv$ 40,000 AU (e.g., compare to the circumstellar disk observed by Torrelles et al. [1996] in Cepheus A with a 300 AU radius). Therefore, it is more likely that either the Class I and II methanol masers are associated in G75.78+0.34, and the H$_2$O masers are part of an outflow or disk of another system (e.g., there is a 4.5 $\mu$m peak near the H$_2$O masers), or that the Class II methanol and H$_2$O masers are associated, and the Class I methanol maser is part of an outflow from another source.

**Figure 4.3:** Diagram of our disk-outflow model 2, showing the locations of the Class II and I methanol masers and the H$_2$O masers. We have chosen to put the information from the G10.47 star forming region (Figure 3.4 and Table 3.2) in this figure. The symbols are the same as those used in Chapter 3, and are marked at the bottom right of the figure. Masers that are blueshifted with respect to the Class II methanol maser are shown in blue.

### 4.2.3 Disk-outflow model 3

Our third model is based on the morphology of methanol and H$_2$O masers in G12.20-0.11, G31.41+0.31, and G35.03+0.35 (§ 3.2.3, § 3.2.4, § 3.2.5, and § 4.1.3). Figure 4.4 shows the model of the disk and outflow, together with the locations of the Class II and Class
I methanol masers and the H$_2$O masers. We have chosen to put the information from G31.41+0.31 (§ 3.2.4) in Figure 4.4. In G31.41+0.31, 5 H$_2$O masers are blueshifted, and 2 H$_2$O masers are redshifted, with respect to the Class II methanol maser (Table 3.4). The Class I methanol maser is blueshifted with respect to the Class II methanol maser, and has a very similar $v_{\text{LSR}}$ to the $v_{\text{LSR}}$ of the H$_2$O masers. Therefore, we have put the Class II methanol maser at the protostar and the Class I methanol maser along with the blueshifted H$_2$O masers in the blueshifted lobe of an outflow in Figure 4.4. Based on the position of the Class I methanol maser and the northern-most blueshifted H$_2$O maser, we get an opening angle for the outflow equal to 22$^\circ$, indicating that the outflow is well collimated. The situation is complicated, however, by the presence of the two redshifted water masers. Clearly, they cannot be in the same outflow as the blueshifted water masers. It is likely, therefore, that they are in the redshifted lobe of a different outflow. Indeed, there is a UC HII region to the northeast, and a 4.5 $\mu$m source to the northwest of the redshifted H$_2$O masers (Figure 3.8), and either could be the source of the redshifted lobe of an outflow.

A similar model works for G35.03+0.35, except that the Class I methanol and the H$_2$O maser are redshifted with respect to the Class II methanol maser (Table 3.5), so we are seeing the redshifted lobe of an outflow in this region. Since there is only one H$_2$O maser, we cannot constrain the opening angle of the outflow. The interpretation is more difficult in G12.20-0.11, where the Class I methanol maser and two H$_2$O masers are redshifted with respect to the Class II methanol maser, but there are now four blueshifted H$_2$O masers (Table 3.3). Again, it is clear that there must be two outflows in this region, and if we associate the redshifted H$_2$O masers and Class I methanol maser with the redshifted lobe of one outflow centered on the protostar near the Class II methanol maser, the blueshifted H$_2$O masers must be in the blueshifted lobe of another outflow. Indeed, there is a 4.5 $\mu$m source to the east of the blueshifted water masers, and another one to the southeast (Figure 3.6), that could be the driving sources of the blueshifted outflow. The opening angles of the outflows are 11$^\circ$ and 19$^\circ$.

In summary, all three of these regions suggest a model in which the Class I methanol maser and the H$_2$O masers are located at the head of outflows where the outflow runs into ambient interstellar material. However, other models where either the Class I and II methanol maser, or one type of methanol maser and H$_2$O maser, are not associated with each other, cannot be ruled out.
Figure 4.4: Diagram of our disk-outflow model 3, showing the locations of the Class II and I methanol masers and the H$_2$O masers. We have chosen to put the information from the G31.41+0.31 star forming region (Figure 3.8 and Table 3.4) in this figure. The symbols are the same as those used in Chapter 3, and are marked at the bottom right of the figure. Masers that are redshifted with respect to the Class II methanol maser are shown in red. The dot-dashed line is meant to be visually suggestive of a bow shock driven into the ambient interstellar material.

4.2.4 Hybrid Model for G45.47+0.07

Our 8th source, G45.47+0.07 (§ 3.2.7 and § 4.1.4) is likely a hybrid of the disk-outflow model 2 (§ 4.2.2) and disk-outflow model 3 (§ 4.2.3). The Class I methanol maser and the H$_2$O maser near it are both redshifted with respect to the Class II methanol maser, so they can be located in the redshifted lobe of an outflow (disk-outflow model 3; § 4.2.3). Meanwhile, the Class II methanol maser and the other H$_2$O maser could be in the disk (disk-outflow model 2; § 4.2.2).
Chapter 5

Conclusion

The primary motivation for this thesis was to find out whether disk-outflow systems are compatible with high mass star formation, based on the existing data on methanol masers, along with other associated tracers of star formation. We searched the literature for high angular resolution data on Class I and Class II methanol masers, H$_2$O masers, UC H II regions, and 4.5 $\mu$m infrared sources. We wanted the highest angular resolution data wherever available, so we looked for VLA (or, even better, VLBI) data. We started with 44 Class I methanol maser sources observed with the VLA and listed in Val’tts & Larionov [2007]. By searching the literature for data around these locations, we obtained high angular resolution data on Class II methanol masers, H$_2$O masers, UC H II regions, and 4.5 $\mu$m infrared sources.

We found a total of thirty regions that contained both Class I and II methanol masers. For twenty two of these regions high angular resolution data were only available on the methanol masers. For these regions, we produced a table of the available data and the projected distances between the Class I and Class II methanol masers (Table 3.9). For the remaining eight regions, high resolution data were available on Class I and II methanol masers, water masers, UC H II regions and 4.5 $\mu$m infrared sources. For these eight regions, we prepared maps of the positions of the Class I and II methanol masers, and the other star formation tracers listed above (§ 3.2.1 - § 3.2.8). We also prepared plots reflecting the center velocities ($v_{\text{LSR}}$) of the Class I and Class II methanol and H$_2$O masers.

Based on these plots, we proposed three disk-outflow models. In all three models, we placed the Class II methanol maser at the location of the protostar, and the Class I methanol maser in the outflow. In our first disk-outflow model (§ 4.2.1), the H$_2$O masers are in a linear pattern delineating the outflow. Two of the eight regions are consistent with this model, although alternative scenarios cannot be ruled out. In our
second disk-outflow model (§ 4.2.2), the H$_2$O masers are located in a circumstellar disk near the Class II methanol maser location; two regions are consistent with this model. In our third disk-outflow model (§ 4.2.3), the H$_2$O masers are located in one or more outflows at the edge of the shocked region where the outflow interacts with the ambient interstellar medium; three regions are consistent with this model. Finally, the 8th region is a hybrid of two of these models with one H$_2$O maser located near the Class I methanol maser in the outflow and another in the circumstellar disk near the Class II methanol maser (§ 4.2.4). All eight regions are therefore compatible with disk-outflow models, with the Class I methanol maser in the outflow, and the Class II methanol maser near the protostar.

Together, these models show the utility of coordinated high angular resolution observations of methanol masers. Since new receivers at 36 GHz are now available at the VLA, there is excellent scope for unique insight into high mass star formation through future observations of Class I and Class II methanol masers.
Appendix A

Astronomical Terms

In this Appendix, we provide brief descriptions of astronomical terms that are used frequently in this thesis. Most of the material in this Appendix is taken from Kraus [1966], unless stated otherwise.

A.1 Right Ascension and Declination

There are at least four different coordinate systems in astronomy. In this thesis, we use the Equatorial Coordinate System. In this system, the Earth’s equator is the plane of reference. Centered at the Earth’s geometric center, we imagine a celestial sphere of arbitrarily large radius on which we represent the objects in the sky (Figure A.1). The celestial sphere is a useful construct borrowed from ancient astronomy, and is due to the inability of our eyes to perceive depth in the sky; that is, all objects in the sky appear to be at the same distance from us, no matter whether they are our neighbors in the Solar System, or objects in the farthest depths of space. The poles of the equatorial coordinate system are at the intersection of the Earth’s axis with the celestial sphere (Figure A.1); they are the North Celestial Pole (NCP) and the South Celestial Pole (SCP). The circle at the intersection of the Earth’s equator and the celestial sphere is called the Celestial Equator. On the celestial sphere, the coordinates of a celestial object such as a star or molecular cloud are expressed in Right Ascension and Declination.

- The Declination is the equivalent of latitude on the celestial sphere. Therefore, the declination is the angle between the celestial equator and the object. It is expressed
in degrees, just like the latitude. The celestial equator is at 0°, and the declination of the poles is +90° (for NCP) and −90° (for SCP). The declination is positive if the object is north of the celestial equator, and negative if south.

- The Right Ascension is the equivalent of longitude on the celestial sphere. It is an angle measured from an arbitrary reference direction (the zero point) to the object’s hour circle. The hour circle of the object is the great circle through the celestial poles and the object (Figure A.1). The arbitrary reference direction, or zero point of right ascension, is the equivalent of the prime meridian for longitude, and it is defined to be the vernal equinox, the point at which the Sun crosses the celestial equator into the northern hemisphere at the beginning of spring. The right ascension is usually specified in hours (h), minutes (m), and seconds (s): the sky appears to turn 360° in 24 hours, or 15° in one hour. So, a right ascension of 1h ≡ 15° at the celestial equator, and 15° cos δ at a declination of δ.

The right ascension and declination of a celestial object define its position in the sky in a relatively fixed manner, independent of the Earth’s diurnal rotation. However, there is a slow change in the equatorial coordinates for a fixed object in the sky over long periods due to a gradual precession of the Earth’s axis around the pole of the ecliptic; this precession makes one cycle in about 26,000 yr. Therefore, it is necessary to explicitly specify the date to which the right ascension and declination refer. This date is called the epoch. In this thesis, we have used the epoch of J2000.0, which means that our stated right ascensions and declinations are the right ascension and declination of the source on January 1, 2000 at noon UT. The “J” stands for Julian, and indicates that we are using the Julian system in which 1 yr is defined to be exactly 365.25 days. Older data with an epoch of B1950.0 (i.e., referred to the right ascension and declination of the source on or about January 1, 1950) have been converted to an epoch of J2000.0, wherever necessary, using standard conversion tools available online. The “B” in B1950 stands for the (now obsolete) Besselian years, in which one year is the period of one complete revolution in right ascension of the fictitious mean Sun, as defined by Newcomb (Section M, Astronomical Almanac, U.S. Naval Observatory).
Figure A.1: Diagram of the celestial sphere depicting how the Equatorial Coordinate System of Right Ascension (RA) and Declination (Dec) is defined. In this system, the Earth’s equator is the plane of reference. Centered at the Earth’s geometric center, we imagine a celestial sphere of arbitrarily large radius on which we represent the objects in the sky. The Right Ascension is the equivalent of longitude on the celestial sphere. The Declination is the equivalent of latitude on the celestial sphere. As shown here, the region G45.07+0.13 ($\S$ 3.2.6) is at RA 19$^h$ 13$^m$ and Dec 10$^\circ$ 51$'$.

A.2 Local Standard of Rest (LSR)

In Galactic studies, motions are usually referred to a Local Standard of Rest, abbreviated as LSR (e.g., Tables 3.1-3.9, where velocities are referenced to the LSR, hence the symbol $v_{\text{LSR}}$). The LSR is defined as the centroid of motion of the stars near the Sun or local region of our home area of the Galaxy (Chandrasekhar 1942). The usual way to calculate the LSR is to calculate the mean velocity of a stellar population, and to correct for any asymmetric drifts (e.g., Binney & Tremaine 1987).

A.3 Intensity and Flux

In this thesis, we frequently use the units of Jy beam$^{-1}$ and Jy. In order to understand these units, it is necessary to understand the difference between the terms intensity (or brightness) of a source and flux, as used in observational astronomy.
Consider an infinitesimal surface area $dA$, with $\theta$ being the angle between the direction of the radiation and the normal to the surface containing $dA$. Consider also an infinitesimal solid angle $d\Omega$ measured at the location of $dA$ (Figure A.2). Then, the energy $dE$ that flows through $dA$ in time $dt$ in the frequency range $\nu$ to $(\nu + d\nu)$ within the solid angle $d\Omega$ at an angle $\theta$ away from the normal to the surface is given by

$$dE_\nu = I_\nu \, d\nu \, dA \cos \theta \, dt \, d\Omega$$

This defines the (monochromatic) intensity $I_\nu$ or brightness, more properly called the specific intensity, spectral intensity, or spectral brightness. That is, the intensity (or brightness) is defined as the energy per unit time (or spectral power) crossing unit area per unit frequency interval into a unit solid angle about the normal to that area. The unit of intensity is, therefore, J s$^{-1}$ m$^{-2}$ Hz$^{-1}$ sr$^{-1}$ or, equivalently, watts m$^{-2}$ Hz$^{-1}$ sr$^{-1}$, where sr (steradian) is the unit of solid angle.

Next, if we write the above equation as

$$\frac{dE_\nu}{dt} = I_\nu \cos \theta \, d\Omega$$

then we get the definition of the flux density as the the energy per unit time (or spectral power) that flows through unit area per unit frequency interval. The terms flux and flux density are often used interchangeably. The unit of flux density is watts m$^{-2}$ Hz$^{-1}$. This is too large for most astronomical sources, so we define:

$$1 \text{ Jansky (Jy)} = 10^{-26} \text{ watts m}^{-2} \text{ Hz}^{-1}$$

Likewise, the unit of intensity is Jy sr$^{-1}$. Since it is inconvenient to convert to sr, astronomers usually write intensity as Jy beam$^{-1}$, where “beam” refers to the beam of the telescope. For interferometers like the VLA, this is the synthesized beam, obtained by dividing the wavelength of the observation by the effective diameter of the interferometer (i.e., the angular resolution). The effective diameter of an interferometer is the separation between the two most distant telescope antennas. For example, in the C-configuration of the VLA, the maximum separation between antennas is about 3.4 km, so the corresponding synthesized beam at an observing frequency of 44 GHz (i.e., 0.7 mm wavelength) would be 0.7 mm/3.4 km, equivalent to 0.5" (e.g., § 3.2.1). For compact (unresolved) sources like the methanol and water masers reported in this thesis, we can measure only the flux density (in Jy), not the intensity (in Jy beam$^{-1}$). However, it is common (but bad) practice to label this as the intensity, and we have done so in this thesis (e.g., Tables 3.1-3.9).
Figure A.2: Diagram showing the geometry for defining intensity and flux. The intensity (or brightness) is defined as the energy per unit time (or spectral power) crossing unit area per unit frequency interval into a unit solid angle about the normal to that area. The radiation is being received in a solid angle $d\Omega$ at an angle $\theta$ to the normal, and is incident on the area $dA$.

A.4 Distance Units in Astronomy

We measure very large distances in astronomy, and the units we use for distances on Earth turn out to be inconvenient. Most astronomers use the parsec (pc), and we have done so throughout this thesis. Formally, a parsec is defined as the distance at which the radius of Earth’s orbit would subtend an angle of one second of arc (Merriam-Webster’s dictionary). An easier to grasp operational definition would be $1 \text{ pc} \equiv 3.26 \text{ Light Years} (\text{Ly})$, where $1 \text{ Ly}$ is the distance traveled by light in 1 year, equal to $9.46 \times 10^{12} \text{ km}$.

On smaller scales, e.g., while discussing the disk in Section $\S$ 4.2.2, one would use the Astronomical Unit, abbreviated as AU. This is the average distance between the Earth and the Sun, defined to be 150 million km. For comparison, $1 \text{ pc} \approx 206,265 \text{ AU}$.

A.5 OB Stars and H II Regions

Young, high mass stars with high luminosity ($L_* \gtrsim 10^4 L_\odot$, where $L_\odot$ is the luminosity of our Sun) and high surface temperature ($T_* \gtrsim 20,000 \text{ K}$) are known as O and B stars.
Regions of photoionized gas around such hot, luminous, young and massive OB stars are known as ionized hydrogen (H II) regions.

There are several categories of H II regions, depending on their observed sizes. In this thesis, we used data for ultracompact (UC) H II regions, and these typically have sizes 0.01-0.1 pc, with typical particle densities $\geq 10^4$ cm$^{-3}$. 
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