A search for radio recombination lines in selected ultra-compact HII regions

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Graduation May 2020
25520776
Declaration of Authorship

I, Molebatsi Potso Treasure, declare that this thesis titled, **A search for radio recombination lines in selected sample of UCHII regions** and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Signed: [Signature]

Date: 21 February 2020
“Aim high and succeed”
Abstract

Faculty of Natural Science
Department of Physics
Magister Scientiae in Astrophysics and Space Science

A search for radio recombination lines in selected ultra-compact HII regions
by Potso Molebatsi

The role that high-mass stars play in galaxies is significant. They strongly affect their environment through their strong ultraviolet radiation, powerful winds, and supernova explosions. The physical processes that control the formation of high-mass stars are not well understood. Hence studying their early evolutionary stages, such as the formation of ultra-compact HII regions, is important in understanding their early evolution. Ultra-compact HII regions are characterized by their small sizes \((d \lesssim 0.1 \text{ pc})\), high densities \((n_e \gtrsim 10^4 \text{ cm}^{-3})\), and high emission measures \((\text{EM} > 10^7 \text{ pc cm}^{-6})\). The study of these regions using observations of radio recombination line emission provides an accurate measure of their physical parameters. This is because radio waves are almost unabsorbed by the interstellar medium and can be detected from very large distances.

In this study, we used the data from the Coordinated Radio and Infrared Survey for High-Mass Star Formation for Southern hemisphere (CORNISH-South), which is a high resolution, high sensitivity radio survey of the southern Galactic plane, to search for radio recombination line emissions (H87α and H112α) on 11 samples of ultra-compact HII regions. The observations were made from December 2010 to January 2012 using the Australian Telescope Compact Array (ATCA) with a receiver covering 4 - 10 GHz range. ATCA simultaneously observe each source for radio continuum and radio recombination line emission. The total integration time for each source was \(\sim 10\) hours. The data were reduced using the Common Astronomy Software Application (CASA), developed for radio astronomy.

We detected four ultracompact HII regions at 3.6 cm and nine were detected at 6 cm. No radio recombination line emission was detected towards any of the ultracompact HII regions in our sample. Hence the physical parameters were derived from the continuum observations. We found the derived physical parameters of these regions are slightly within \(2\sigma\) of those derived by Wood & Churchwell (1989) and Kurtz et al. (1994). Using the continuum parameters, we then derived the expected parameter for the radio recombination line emissions. We found that the line emission in these regions could possibly have widths \(> 25\) km/s and have low intensities. This could be the main reason why we detect no radio recombination line emission.

Keywords: High-mass star formation; Ultracompact HII region; Radio recombination lines; Radio continuum; Interferometry
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## Abbreviations

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<th>Abbreviation</th>
<th>Full Form</th>
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<tbody>
<tr>
<td>2MASS</td>
<td>Two Micron All-Sky Survey</td>
</tr>
<tr>
<td>AGN</td>
<td>Active Galactic Nuclei</td>
</tr>
<tr>
<td>ATCA</td>
<td>Australian Telescope Compact Array</td>
</tr>
<tr>
<td>ATLASGAL</td>
<td>APEX Telescope Large Area Survey of the Galaxy</td>
</tr>
<tr>
<td>BGPS</td>
<td>Bolocam Galactic Plane Survey</td>
</tr>
<tr>
<td>CASA</td>
<td>Common Astronomy Software Application</td>
</tr>
<tr>
<td>CABB</td>
<td>Compact Array Broad-band Backend</td>
</tr>
<tr>
<td>CORNISH</td>
<td>Coordinated Radio and Infrared Survey for High-Mass Star Formation</td>
</tr>
<tr>
<td>EM</td>
<td>Emission Measure</td>
</tr>
<tr>
<td>FCRAO</td>
<td>Five College Radio Astronomy Observatory</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width Half Maximum</td>
</tr>
<tr>
<td>GPS</td>
<td>Galactic Ring Survey</td>
</tr>
<tr>
<td>GLIMPSE</td>
<td>Galactic Legacy Infrared Midplane Survey Extraordinaire</td>
</tr>
<tr>
<td>IR</td>
<td>Infrared</td>
</tr>
<tr>
<td>IRAS</td>
<td>Infrared Astronomical Satellite</td>
</tr>
<tr>
<td>HII</td>
<td>Ionized Hydrogen</td>
</tr>
<tr>
<td>HCHII</td>
<td>Hyper compact Ionized Hydrogen</td>
</tr>
<tr>
<td>ISM</td>
<td>Interstellar Medium</td>
</tr>
<tr>
<td>LTE</td>
<td>Local Thermal Equilibrium</td>
</tr>
<tr>
<td>MSX</td>
<td>Midcourse Space Experiment</td>
</tr>
<tr>
<td>RMS</td>
<td>Red MSX Survey</td>
</tr>
<tr>
<td>RRL</td>
<td>Radio recombination lines</td>
</tr>
<tr>
<td>SNR</td>
<td>signal-to-noise</td>
</tr>
<tr>
<td>UC</td>
<td>Ultracompact</td>
</tr>
<tr>
<td>UKIDSS</td>
<td>UKIRT Infrared Deep Sky Survey</td>
</tr>
<tr>
<td>VLA</td>
<td>Very Large Array</td>
</tr>
</tbody>
</table>
Physical Constants

Speed of Light \( c = 2.997 \, 924 \, 58 \times 10^8 \text{ ms}^{-8} \)

Ionization cross-section \( \sigma_0 = 6 \times 10^{-18} \text{ cm}^2 \)

Rydberg constant \( R = 3.2898 \times 10^{-15} \text{ Hz} \)

Electron mass \( m = 9.1094 \times 10^{-31} \text{ kg} \)

Planck’s constant \( h = 6.6261 \times 10^{-34} \text{ J s} \)

Boltzmann constant \( k = 1.3807 \times 10^{-23} \text{ J/K} \)
Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>$\nu$</td>
<td>frequency</td>
<td>Hz</td>
</tr>
<tr>
<td>$\sigma_\nu$</td>
<td>ionization cross-section</td>
<td>cm$^{-2}$</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature</td>
<td>K</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>wavelength</td>
<td>m</td>
</tr>
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Chapter 1

Introduction

High-mass stars (M > 8 M⊙) play an important role in the Galaxy. They emit strong ultraviolet with photons energies $h\nu > 13.6$ eV, enough to ionize their surrounding gas and form ionized hydrogen (HII) regions. High-mass stars also have extremely powerful winds that inject momentum and mechanical energy into the interstellar medium (ISM), and they die through supernova explosions that destroy and enrich the surrounding environment with heavy elements. They also heat-up and destroy the molecular clouds from which they formed and modify the chemistry within their surrounding (Osterbrock 1989; Tielens 2005). Because of such a dominant role in the Galaxy, they affect the physical state of the ISM which is responsible for the rate of the formation and composition of the next generation of stars. It is therefore important to understand the conditions that give rise to the formation and early evolution of high-mass stars.

One of the early evolutionary stages of high-mass star formation is indicated by the detection of ultracompact (UC) HII regions. The UCHII regions are formed by young high-mass stars (O and early B type stars) still embedded in their natal molecular clouds. These regions are characterized by their small sizes (diameter $\lesssim 0.1$ pc), high electron densities ($n_e \gtrsim 10^4$ cm$^{-3}$) and high emission measures (EM $> 10^7$ pc cm$^{-6}$). They are difficult to observe at wavelengths other than radio and infrared (IR) wavelengths because at short wavelengths the dense molecular clouds surrounding them absorbs all the photons (Stahler & Palla 2005). However, at IR the dust absorbs the photons and re-radiate them at near-IR wavelengths, and at radio wavelengths there is little obscuration of photons.
Ultracompact HII Region Morphologies

**Figure 1.1:** An illustration of the basic ultracompact HII region morphologies adapted from Wood & Churchwell (1989).
Table 1.1: Types of HII regions and thier physical parameters (Franco et al. 2000; Kurtz 2002).

<table>
<thead>
<tr>
<th>Types of regions</th>
<th>Size (pc)</th>
<th>Density (cm$^{-3}$)</th>
<th>EM (pc cm$^{-6}$)</th>
</tr>
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<tbody>
<tr>
<td>Hypercompact</td>
<td>$\sim 0.003$</td>
<td>$\gtrsim 10^6$</td>
<td>$\gtrsim 10^9$</td>
</tr>
<tr>
<td>Ultracomact</td>
<td>$\lesssim 0.1$</td>
<td>$\gtrsim 10^4$</td>
<td>$\gtrsim 10^7$</td>
</tr>
<tr>
<td>Compact</td>
<td>$\lesssim 0.5$</td>
<td>$\gtrsim 5 \times 10^3$</td>
<td>$\gtrsim 10^7$</td>
</tr>
<tr>
<td>Classical</td>
<td>$\sim 10$</td>
<td>$\sim 100$</td>
<td>$\sim 10^2$</td>
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Wood & Churchwell (1989) used the Infrared Astronomical Satellite (IRAS) point sources whose far-infrared colors are similar to that of high-mass star-forming regions with known associated UCHII regions. Their study together with that of Kurtz et al. (1994) significantly increased the number of known UCHII regions and became fundamental for studies of UCHII regions. Wood & Churchwell (1989) and Kurtz et al. (1994) identified five morphological types of UCHII regions which are cometary, shell, core-halo, spherical or unresolved, and irregular (or multiply peaked). Figure 1.1 shows a schematic for all these morphologies. Churchwell (2002) identified another morphology type called bipolar. All these morphologies are different from the standard ideal morphology (Strömgren sphere) discussed by Strömgren (1939).

The UCHII regions represent a particular stage of the high-mass star evolution, see Table 1.1. It is difficult to observe all evolutionary stages of high-mass stars because they evolve quickly while embedded within dense molecular clouds. There are several theories trying to explain the evolution of these stars (Shu et al. 1987; Bonnell et al. 2001; McKee & Tan 2003; Zinnecker & Yorke 2007; Tan et al. 2014; Krumholz 2015). However, over the past years, progress have been made in the study of high-mass star formation through a number of multi-wavelength surveys of high-mass star forming regions (Churchwell et al. 2009; Schuller et al. 2009; Hoare et al. 2012).

Surveys are a big help in studying the Galaxy at different frequencies. Here we focus on IR and radio surveys and their impact on the understanding of star formation. We consider surveys such as the Galactic Legacy Infrared Midplane Survey Extraordinaire v 1.0 (GLIMPSE I) (Churchwell et al. 2009), which is the Spitzer IRAC Legacy Programme. It has cataloged sources with hot circumstellar dust emission such as young and evolved stars. This survey covered a significant fraction of the entire sky at 3.6, 4.5, 5.8, and 8.0 µm with an angular resolution of 1.4$''$ – 1.9$''$ which is better than any previous mid-IR survey. The UKIRT Infrared Deep Sky Survey (UKIDSS) (Lawrence et al. 2007) program is a deep near-IR Galactic plane survey with a sensitivity of about 3 mag and 2-3 times better resolution than the Two Micron All-Sky Survey (2MASS) (Skrutskie et al. 2006). Near-IR surveys are important in mapping the extinction mostly in molecular clouds. Jackson et al. (2006) traced the distribution and dynamics of the cold molecular gas using $^{13}$CO (1-0) Boston University Galactic Ring Survey (GPS) from Five College Radio Astronomy Observatory (FCRAO), 14 m telescope covering a galactic longitude range of $l = 18^\circ – 55.7^\circ$ and galactic latitude range of $|b| < 1^\circ$ with angular resolution of 46$''$. The submillimeter survey such as the APEX Telescope Large Area Survey of the Galaxy (ATLASGAL) (Schuller et al. 2009) and the Bolocam Galactic Plane Survey (BGPS) (Aguirre et al. 2011) mapped the cold dust from these molecular clouds.
These multiwavelength surveys of the Galactic plane are missing surveys with high resolution and high sensitivity for the study of ionized gas. Existing surveys (e.g. White et al. (2005) and Giveon et al. (2005)) does not have the resolution or coverage to complete the picture of the Galaxy. Hence, Hoare et al. (2012) conducted a radio continuum survey of the inner Galactic plane at 5 GHz with arcsecond resolution and 2 mJy sensitivity. The survey is called the Coordinated Radio and Infrared Survey for High-Mass Star Formation (CORNISH) and it complements other Galactic plane surveys such as the Midcourse Space Experiment (MSX) (Egan et al. 2003), GLIMPSE, and ATLASGAL. The aim of CORNISH is to provide an unbiased survey for UCHII regions which will help in the study of high-mass star formation. It also focuses on evolved stars, active stars and binaries, and extragalactic sources. The CORNISH survey is designed to simultaneously observe radio continuum and radio recombination lines (RRL).

RRLs are important in the study of warm ($10^4$ K), ionized gas associated with high-mass star formation. Their emissions are free from extinction and can be used to study objects that are obscured. RRLs have been used extensively as probes of the physical conditions in HII regions (Churchwell et al. 1990; Roelfsema & Goss 1992; Kim & Koo 2001). Because they are not attenuated by interstellar dust along the line of sight, their observed line parameters, such as intensity and velocity, can be interpreted directly in terms of the properties of the emitting gas without having to apply model-dependent corrections for interstellar extinction. RRLs will be discussed in the next chapter.

**Motivation for this study**

We have yet to understand the physics that controls the formation of high-mass stars and how the feedback processes affect further star formation. Currently, there is no theory which predicts how many stars and of what type will form from a given mass of gas in a particular environment. In many cases (Churchwell 2002), it appears that further star formation occurs in the dense gas around UCHII regions. Hence, we need to study large, well-selected samples of these regions to have a firm statistical basis. This is best done using the radio free-free (continuum) emission from the UCHII regions which can be seen right across our Galaxy.

In this study we uses the data from the CORNISH-South survey which is a high resolution, high sensitivity radio survey of the southern Galactic plane. The survey have both continuum data to identify a complete sample of UCHII regions and spectral line data to study their dynamics. The aim of our study is to compile a sample of southern UCHII regions and derive their physical parameters.
Chapter 2

HII regions and radio recombination lines.

2.1 HII regions

An ionized hydrogen (HII) region is a region in space formed when hydrogen gas is ionized by photons with energies $\geq 13.6$ eV. Such photons are produced by several types of objects such as high-mass stars, hot dying lower-mass stars, or active galactic nuclei (AGN). High-mass stars (i.e. stars with solar masses $M_\odot \geq 8$) emit copious amounts of photons that can ionize their surrounding gas. These stars have a surface temperature of $T > 10000$ K, enough to produce photons with energies $\geq 13.6$ eV. Hot dying low-mass stars have temperatures of about $\sim 25000$–$200000$ K and they are central objects to the planetary nebulae with temperatures of $\sim 10000$ K (Kwok 2000). The photons within the nebulae have energies capable of doubly ionizing helium to create the HeIII zone. However, in this study, we focus on the HII regions caused by high-mass stars.

High-mass stars emit photons that ionize the surrounding gas and form HII regions. The ionized gas or HII regions consist of the free electrons, ions, and atoms. A fully ionized HII region only has free electrons and ions. The free electrons occasionally recombine with the ions to form excited atoms. The degree of ionization is determined by the balance between photoionization and recombination. Thus, the ideal size of the HII region can be derived from the condition of photoionization equilibrium.

Assume the gas to consists of only pure hydrogen gas. The photoionization equilibrium is then given as

$$N_{H^0} \int_{\nu_0}^{\infty} \frac{4\pi J_\nu}{h\nu} \sigma_\nu d\nu = N_i N_e \alpha_{rec}. \quad (2.1)$$

where $\nu_0$ is the ionization threshold frequency, $\sigma_\nu$ is the ionization cross-section, $\alpha_{rec}$ is the recombination rate coefficient, $J_\nu$ is the mean intensity of the ionizing photons, and $N_{H^0}$, $N_i$, and $N_e$ are the number densities for neutral hydrogen, ions, and electrons, respectively. The left hand side represent the volumetric ionization rate, which is the number of neutral hydrogen atoms per unit volume $\times$ the
flux of ionizing photons $\times$ the ionization cross-section. The right hand side represent the volumetric recombination rate, which is the number of ions per unit volume $\times$ the number of free electrons per unit volume $\times$ recombination coefficient.

The ionization cross-section, $\sigma_\nu$, determines how far the photons can penetrate the gas, and it is given by

$$\sigma_\nu = \sigma_0 \left( b \left( \frac{\nu}{\nu_0} \right)^{-a} + (1 - b) \left( \frac{\nu}{\nu_0} \right)^{-a-1} \right) \quad \nu > \nu_0,$$

where $a$ and $b$ are fitting parameters given by Osterbrock (1989) and Tielens (2005). The ionization cross-section $\sigma_\nu$ is measured in square centimeter ($\text{cm}^2$) and $\sigma_0 = 6 \times 10^{-18} \text{ cm}^2$. Equation 2.2 accounts for all the elements as shown in Figure 2.1. Figure 2.1 show that the ionization cross-section for “simple” elements such hydrogen and helium peaks at the ionization threshold frequency $\nu_0$ and decreases as $\nu^{-3}$. For heavy elements such as oxygen which has ionization at different levels of ion and inner shell ionization, the ionization cross-section can be more complex than that given in Equation 2.2.

Assuming that the HII region is fully ionized, the ionizing photon flux in Equation 2.1, at frequency $\nu$ is

$$\frac{4\pi J_\nu}{h\nu} = \frac{1}{4\pi r^2} \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu,$$  

Figure 2.1: Ionization cross-section for hygron, helium and oxygen.
where \( L_\nu \) is the luminosity per unit frequency interval and

\[
\int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu = Q(H^0),
\]

(2.4)

which is the total number of ionizing photons emitted by the central source. Integrating Equation 2.1 over \( r \), where \( r \) is the distance from the central source to the point in question, yields

\[
Q(H^0) = \frac{4}{3} \pi r^3 N_e^2 \alpha_B.
\]

(2.5)

If we assume that the HII region have uniform density then \( N_i \approx N_e \approx N(H) \). The photons emitted when the transition is directly to ground level have energies of 13.6 eV which are absorbed approximately on the spot. The recombination rate coefficient, \( \alpha_B \), is for all recombinations except recombinations directly to the ground state. Hence, such recombinations are neglected. The radius of the HII regions is then given by

\[
r = \left( \frac{3Q(H^0)}{4\pi N_e^2 \alpha_B} \right)^{1/3}
\]

(2.6)

where \( r \) is known as Strömgren radius (Strömgren 1939), which is an ideal sphere of the HII regions with the ionizing star of spectral type O (or early B) at the center of the sphere. Figure 2.2 shows an HII region with the ionizing star of spectral type O emitting photons capable of ionizing hydrogen and helium as shown by \( R_H \) and \( R_{He} \), respectively. The neutral density hydrogen gas is represented by \( H^0 \). A fully derivation of Strömgren radius, Equation 2.6, is given by Wilson et al. (2009).

HII regions are found in dense areas and are observed through their continuum emission spectra which are detectable at long wavelengths. The continuum emission is produced by bound-free, two-photon, and free-free processes. The bound-free emission comes from recombination; the two-photon process is from hydrogen transitions from \( n = 2, l = 2 \) levels to \( n = 0, l = 0 \) ground state. The free-free emission or bremsstrahlung comes from the interaction of free electrons and ions. We will focus on free-free emission because it is the more dominant radiation at radio wavelengths. HII regions are also defined by the emission lines produced when excited atoms decay or transition down to ground level.

### 2.2 Radio recombination line

Radio recombination lines emissions are produced when free electrons combine with ions giving rise to atoms in an excited state \( (n \geq 40) \). A series of radio recombination lines emissions are emitted as the electron cascades down to the ground state. According to the Bohr model (Wilson et al. 2009), each of the lines in the series have discrete frequencies represented by

\[
\nu = R_c Z^2 \left( \frac{1}{n^2} - \frac{1}{(n + \Delta n)^2} \right),
\]

(2.7)
Figure 2.2: A simple illustration of a HII region caused by O type star which emits photons capable to ionize hydrogen and helium gas. (Roelfsema & Goss 1992).

where $n$ is a positive integer representing the energy level, $c$ is the speed of light, $Z$ is the nuclear charge, and the constant $R = \frac{2\pi^2me^4}{\hbar^3c}$ is called the Rydberg constant. The line series can be identified by choosing the value of $n$, and $\Delta n = 1, 2, 3, ..., etc$ which correspond to $\alpha, \beta, \gamma, ..., etc$. For hydrogen these lines are grouped. For example, if $n = 1$ the transitions would give the Lyman series, and if $n = 2$ the Balmer series, and $n = 3$ the Paschen series, and so on.

The line transitions are detectable at different wavelength ranges depending on their energy level. For $n > 40$, the transitions are detectable at radio wavelengths as radio recombination line emission (Roelfsema & Goss 1992). The transition from $(n + \Delta n) \rightarrow n$ for species $X$ is denoted by $Xn\Delta n$. For example, H109$\alpha$ is the hydrogen transition from level 110 to 109, and He137$\beta$ is the helium transition from level 138 to 137. Figure 2.3 show a recombination line spectrum with more than one element. Each element has its line frequency given by Equation 2.7, some elements have their line frequencies close to each other as shown in the Figure 2.3 by He109$\alpha$ and C109$\alpha$. 

2.3 Radiation propagation through an HII region

The emission traveling through the HII regions comprises free-free emission and line emission, and the equation of transfer allows us to understand the propagation of these emissions.

2.3.1 Transfer equation

The photons or radiation emitted by the source (HII region) carries information such as the location of the source and the characteristics that can identify its origin and describes its environment. The radiation is being absorbed and emitted as it travels through the ISM. This change is described by the equation of transfer

\[ \frac{dI_\nu}{ds} = -\kappa_\nu I_\nu + j_\nu, \] \hspace{1cm} (2.8)

where \( s \) is the distance the radiation travels towards the observer (see Figure 2.4), \( \kappa_\nu \) is the absorption coefficient which accounts for all depletions from the radiation in the direction of the observer, \( j_\nu \) is the emission coefficient which accounts for all the gains, and \( I_\nu \) is the specific intensity (or brightness) defined as the radiant energy per unit time per unit collection area per unit bandwidth interval per unit solid angle (Wilson et al. 2009).

In the Figure 2.4, the medium is depicted by the cylinder with infinitesimal length \( ds \) and area \( d\sigma \). The source intensity is \( I_\nu(s) \) before the radiation passes through the medium. Inside the medium, the radiation is absorbed, scattered, and the medium emit its own radiation which would add to the original radiation. The intensity of the radiation that leaves the medium and traveling towards observer is \( I_\nu(s + ds) \).
The intensity as seen by the observer is given by \(^1\)
\[
I_\nu(s) = I_\nu(0)e^{-\tau_\nu(s)} + \int_0^{\tau_\nu(s)} \frac{j_\nu}{\kappa_\nu} e^{-\tau_\nu} d\tau.
\] (2.9)

The first term is the background radiation attenuated as it passes through the medium. The second term describes the contribution to \(I\) by the medium. The ‘optical depth’ \(\tau_\nu\) is defined as
\[
d\tau_\nu = -\kappa_\nu ds.
\] (2.10)

The ratio \(\frac{j_\nu}{\kappa_\nu}\) in Equation 2.9 is called the source function and is symbolized by \(S\). It defines the ratio of photons being emitted to those being absorbed from \(I_\nu\) to each point along the radiation path. In a thermodynamic equilibrium medium, i.e. in an enclosure where no photons can escape, Kirchhoff’s law of thermodynamics state that
\[
j_\nu = \kappa_\nu B_\nu(T).
\] (2.11)

\(T\) is the temperature of the medium. The function \(B_\nu(T)\) is the Planck function and is given by
\[
B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1},
\] (2.12)

where \(h\) and \(k\) are Planck’s and Boltzmann’s constants, respectively. If \(h\nu \ll kT\),
\[
B_\nu(T) = \frac{2\nu^2kT}{c^2},
\] (2.13)

this is called Rayleigh-Jean approximation to the Planck function and it usually occurs in the radio range. If \(h\nu \gg kT\),
\[
B_\nu(T) = \frac{2\nu^3}{c^2} e^{-h\nu/kT},
\] (2.14)

is called Wien’s approximation to the Planck function and usually occurs in the optical range.

\(^1\)The full derivation is shown in the Tools of Radio Astronomy (Wilson et al. 2009).
In an isothermal medium, Equation 2.9 can be expressed as

\[ I_\nu(s) = I_\nu(0)e^{-\tau_\nu(s)} + B_\nu(T_e)(1 - e^{-\tau_\nu(s)}). \] (2.15)

If there is no background radiation \((I_\nu(0) = 0)\), there are two limiting cases often considered:

- in an optical thick medium, \(\tau \gg 1\), the Equation 2.15 approaches

\[ I_\nu(s) = B_\nu(T_e) \] (2.16)

the medium is in local thermodynamics equilibrium (LTE).

- In an optical thin medium, \(\tau \ll 1\), the Equation 2.15 approaches

\[ I_\nu(s) = \tau_\nu B_\nu(T_e). \] (2.17)

Thus, the emission from an optically thin medium is always less than that of an optically thick medium. It is a common practice in radio astronomy to measure the intensity of radiation, Equation 2.9, in terms of its brightness temperature \((T_b)\) which is the temperature that is equivalent to the black body temperature as defined by Rayleigh-Jean in Equation 2.13. Substituting Equation 2.13 into Equation 2.9 will result in

\[ T(s) = T(0)e^{-\tau_\nu(s)} + T(1 - e^{-\tau_\nu(s)}). \] (2.18)

### 2.3.2 Free-free radiation

Free-free radiation are produced by free particles interacting and their energy state is not quantized, but continuous. That is, as the free electrons find their way inside the HII region, there is bremsstrahlung emission produced by collision of free electrons and ions. The emission coefficient is given by

\[ j_\nu = \frac{4}{3} \frac{Z^2 e^6 N_i N_e}{c^5} \frac{m^2}{\pi^2 k T} \ln \frac{p_2}{p_1} \sqrt{\frac{2m}{\pi k T}} \ln \frac{p_2}{p_1} \] (2.19)

where \(p_1\) and \(p_2\) are collision parameters, and \(m\) is the electron mass. The absorption coefficient can be obtained from Kirchhoff’s law. Oster (1961) gives an expression for the absorption coefficient as

\[ k_\nu = \left( \frac{n_i n_e}{\nu^2} \right) \left( \frac{8 Z^2 e^6}{3 \sqrt{3} m^3 c} \right) \left( \frac{\pi}{2} \right)^{1/2} \left( \frac{m}{k T} \right)^{3/2} \langle g \rangle, \] (2.20)

where \(\langle g \rangle\) is the Gaunt factor given as

\[
\langle g_{ff} \rangle = \begin{cases} 
\ln \left[ 4.955 \times 10^{-2} \left( \frac{\nu}{\text{MHz}} \right)^{-1} \right] + 1.5 \ln \left( \frac{T_e}{K} \right) & \text{for } \frac{\nu}{\text{MHz}} \gg \left( \frac{T_e}{K} \right)^{3/2} \\
1 & \text{for } \frac{\nu}{\text{MHz}} \ll \left( \frac{T_e}{K} \right)^{3/2}.
\end{cases}
\]
Wilson et al. (2009) give the full derivation of these coefficients. Mezger & Henderson (1967) used Oster (1961) and Altenhoff et al. (1960) expressions to derive the optical depth of an HII region as

$$\tau_C = 8.235 \times 10^{-2} a T_e^{-1.35} \nu^{-2.1} EM$$

(2.21)

where $EM$ is the emission measure defined as

$$\frac{EM}{\text{pc cm}^{-6}} = \int_0^s \left( \frac{n_e}{\text{cm}^{-3}} \right)^2 d\left( \frac{s}{\text{pc}} \right),$$

(2.22)

The factor $a$ in Equation 2.10 is given as $a = \frac{\tau_C(\text{Oster})}{\tau_C(\text{AMWW})} = 0.366 \nu_{GHz}^{0.11} T_e^{-0.15} \times [\ln(4.995 \times 10^2 \nu_{GHz}^{-1}) + 1.5\ln(T_e)],$ but it is usually assumed as $a \approx 1.$

Figure 2.5 shows the spectral energy distribution of an HII region following Equation 2.15. The region is assumed to have an electron temperature $T_e \sim 10^4$ K and emission measure $EM \sim 10^7$ pc cm$^{-6}$. The vertical line $\nu_0$ indicates the turn-over frequency, which is the frequency at what $\tau_C = 1$, and is given as

$$\frac{\nu_0}{\text{GHz}} = 0.3045 \left( \frac{T_e}{K} \right)^{-0.643} \left( a \frac{EM}{\text{pc cm}^{-6}} \right)^{0.476}.$$  

(2.23)

This region is optically thick ($\tau \gg 1$) for $\nu \ll \nu_0$ and optically thin ($\tau \ll 1$) for $\nu \gg \nu_0$. 
2.3.3 Line radiation

The equation of transfer can also be expressed in terms of the Einstein coefficients (Wilson et al. 2009),

\[
\frac{dI_\nu}{ds} = -\frac{h\nu}{c} (N_1 B_{12} - N_2 B_{21}) I_\nu \phi(\nu) + \frac{h\nu}{4\pi} N_2 A_{21} \phi(\nu) \tag{2.24}
\]

where \( B_{12}, B_{21} \) and \( A_{21} \) are the Einstein coefficients, \( N_i \) is the number density in the state \( E_i \), and \( \phi(\nu) \) is the line profile function. According to Einstein (1916), there are different transition probabilities per unit time between excited level \( E_2 \) and the lower level \( E_1 \). The probability per unit time of an electron to spontaneously transition to a lower energy level is represented by \( A_{21} \). When a photon causes an electron to decay to a lower energy level releasing a photon of the same energy which triggered the decay, the emission is called stimulated emission and its probability per unit time is \( B_{21} \bar{U} \), where \( \bar{U} \) is the average energy density of the radiation field. The probability per unit time of a photon to excite an electron from a lower energy level to higher energy level is \( B_{12} \bar{U} \).

By comparing the Equation 2.24 to Equation 2.8, the emission coefficient can be written as

\[
j_L = N_2 \frac{h\nu}{4\pi} A_{21} \phi(\nu), \tag{2.25}
\]

and the absorption coefficient as

\[
k_L = \frac{c^2}{8\pi\nu_0^2} g_i N_1 A_{21} \left[ 1 - \frac{b_2}{b_1} e^{-\frac{h\nu}{kT_e}} \right] \phi(\nu), \tag{2.26}
\]

where \( g_i \) is the statistical weight of energy level \( i \) and \( b_i \) is the departure coefficient from LTE.

The optical depth at the center of the line is

\[
\tau_L = 1.92 \times 10^{-3} T_e^{-5/2} \Delta \nu^{-1} EM, \tag{2.27}
\]

and the peak line brightness temperature is given by

\[
T_L = 1.92 \times 10^{-3} T_e^{-3/2} \Delta \nu^{-1} EM. \tag{2.28}
\]

The free-free and line emission relate through the line-to-continuum ratio obtained by dividing Equation 2.27 and 2.21 and taking into account the Doppler relation, and

\[
\frac{T_L}{T_C} \Delta \nu = \frac{6.985 \times 10^3}{a(T_e, \nu)} \nu_{GHz}^{1.1} T_e^{-1.15} \frac{1}{1 + \frac{N(He^+)}{N(H^+)}} \tag{2.29}
\]

where \( \Delta \nu \) is the line width in km s\(^{-1}\). Under special conditions, \( T_L/T_C \approx \nu^{1.1} \) and \( T_L \approx \nu^{-1} \), i.e. the brightness temperature amplitude of the RRL decreases with increasing frequency. To maximize \( T_L \), we must observe at lower frequencies which is above the turnover frequency \( (\tau = 1) \), otherwise, the object becomes optically thick and no line will be detected (Wilson et al. 2009).
Chapter 3

Observations and Data Reduction

3.1 Interferometry

Each wavelength range in the electromagnetic spectra is uniquely important to the understanding of the Universe. The radio wavelength range is important for several reasons: 1) we can perform radio observations from the ground, 2) we can detect some objects with great sensitivity at radio wavelengths, and 3) we can get quantitative physical information about the conditions in sources that emit radio emission. The radio telescopes have limited spatial resolution (or angular resolution) given by

$$\theta \sim \frac{\lambda}{D} \text{ [radians]}$$

where $D$ is the diameter of the telescope and $\lambda$ is the observed wavelength. For example, the largest steerable single radio telescope is the Green Bank Telescope with a 110 m diameter and its angular resolution at a wavelength of 6 cm is about 2 arcminutes. To observe certain radio sources, we need a better resolution. Hence, radio interferometry becomes important. The radio interferometer is an array of single telescopes (or antennas) working together to form a single telescope with an angular resolution given by

$$\theta = \frac{\lambda}{B} \text{ [radians]}, \quad (3.1)$$

where $B$ is the maximum separation (or baseline length) between the antennas. The Australian Telescope Compact Array (ATCA), is an example of a radio interferometer. It has a maximum baseline of 6 km and its angular resolution at 6 cm is about 2 arcseconds.

A radio interferometer measures the complex visibilities (amplitude and phase) of a source, which is the Fourier transform of the source brightness distribution on the sky. To understand this process, it is best to simplify the interferometer of $N \gg 2$ antennas with $N(N-1)/2$ baselines to only two
antennas with a single baseline. We call this a two-element interferometer as illustrated in Figure 3.1. Where two antennas point toward the same distant source in a direction shown by the unit vector \( \mathbf{s} \). The baseline vector \( \mathbf{B} \) separates the antennas. Because of the positions of the antennas and the position of the source, the incoming signal would reach each antennas at a different time. The delayed time is called the geometric time delay and is given by

\[
\tau_g = \frac{\mathbf{B} \cdot \mathbf{s}}{c},
\]

where \( c \) is the speed of light. A schematic of a two-element interferometer is shown in Figure 3.1, where the signal from each antenna passes through an amplifier which selects required observing frequency with a bandwidth \( \Delta \nu \) centered on frequency \( \nu \). The correlator will combine the signals.
The correlator also multiplies and time-average the signals. If the signal for antennas at time $t$ is given by

$$V_1(t) = V \cos[2\pi \nu (t - \tau_g)] \quad \text{and} \quad V_2(t) = V \cos(2\pi \nu t),$$

(3.3)

the output response of the correlator is given by

$$R_c = \langle V_1V_2 \rangle = \left( \frac{V}{2} \right) \cos(2\pi \nu \tau_g),$$

(3.4)

where $\left( \frac{V^2}{2} \right)$ is directly proportional to the spectral power density of the radio source as measured by the interferometer.

If we express the signal as the radio brightness distribution integrated over the solid angle of the source, we would write the interferometer response as
\[ V(u, v) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} A(l, m) I(l, m) e^{-2\pi i (ul + vm)} \, dl \, dm. \]  

(3.5)

Where \( I(l, m) \) is the radio brightness distribution, \( A \) is the normalized effective collecting area. \( V(u, v) \) is also called complex visibility in the coordinate system shown in Figure 3.2. In the Figure 3.2 \((u, v, w)\) represent the baseline vector components where \( w \) points towards an object of interest. These components are measured in wavelengths. The sky positions is defined by \((l, m, n)\) components which are direction cosines measured with respect to \(u\) and \(v\) axes. Perley et al. (1989) show the full derivation of Equation 3.5. By inverse Fourier transform Equation 3.5 we can get the brightness distribution \( I(l, m) \).

### 3.1.1 Calibration

Several factors can alter the interferometer measurement (visibility) such as atmospheric attenuation, phase error, delay error, amplitude error, a bad position and wide bandwidth, and non-identical electronics/gains. The Radio Interferometer Measurement Equation (RIME) relates the measured (or observed) visibility to the true visibility. The RIME is given by

\[ \bar{V}_{ij}^{\text{obs}} = J_{ij} \bar{V}_{ij}^{\text{IDEAL}} \]  

(3.6)

where

\[ J_{ij} = J_i \times J_j^s \] is the Jones matrix for antenna i and j.

The Jones matrix describes the antenna-based calibrations, for each correlation, for a given correction e.g. (gain, bandpass, delay, etc). To solve for calibration, it requires a model of the sky. Here is the basic strategy for calibration:

- Observe the targeted source
- observe a gain calibrator, which solves the atmospheric and instrumental errors with time. It corrects the phase as a function of time.
- Observe a bandpass calibrator, which solves the instrumental errors with frequency. It corrects the phase as a function of frequency.
- Observe a flux calibrator, which is a bright source with a known flux density. It corrects for amplitude.

We apply the solution from the calibration to the data to approximate the true visibility. Even after calibration there are some residual errors in data that might be because of the different time
calibration were observed or the position of the target source on the sky. To correct for this, self-
calibration is performed (Perley et al. 1989), which is where the source is used as a model and solves
for calibration. There are two types of self-calibration: 1) phase and 2) amplitude and phase. Phase
calibration requires a source to have a signal-to-noise $S/N > 3$. For amplitude self-calibration, it
requires a source to have $S/N > 10$. Here is the strategy for self-calibration:

- makes an image of the target source after applying calibration solutions,
- use the image of the target source in step 1 as a source model to calibrate the data over some
  solution interval,
- iterate this process until the noise (rms) level in the image does not change anymore.

Self-calibration can be helpful because it can correct for residual amplitude and phase errors, and
it can correct for direction-dependent effects. However, it can also be disadvantageous in such that
errors in the model or low SNR can propagate into the self-calibration solution and diverge from the
correct model.

### 3.1.2 Deconvolution

The visibility $(V(u,v))$ can not be completely sampled the u-v plane. $S(u,v)$ represents the sampled
points. The Fourier transform of the sample visibility function $V(u,v)S(u,v)$ yields $I^D(l,m)$ which
referred to as dirty image or dirty map. Using the convolution theorem, the dirty image $I^D(l,m)$
is the convolution of true image (the true sky brightness) and the dirty beam (which is the the
Fourier transform of $S(u,v)$ also known as point-spread function). The true image or the true
sky brightness is obtained by deconvolution. The sampling function ($S(u,v)$) can be modified by
introducing weightings ($W(u,v)$) which changes the shape of the dirty beam. There are different
types of weightings: natural, uniform, robust, and tapering. In radio astronomy, the algorithm that
deconvolves the dirty image is called CLEAN and can be performed by different software applications
(e.g CASA). The algorithm is called Högboom algorithm and proceed as follows:

1. it identifies the strength and position of the peak in the dirty image,
2. subtract some fraction of the peak (dirty beam $\times$ gain) from the dirty image and store its
   position and intensity in as a CLEAN component
3. repeat step 1 until the flux levels in the image reaches the pre-set (or required) stopping level.

An approximation of the true image is obtained after the last step.
3.2 Australian Telescope Compact Array

ATCA is a radio interferometer at the Paul Wild Observatory near Narrabri, 550 km north-west of Sydney. It comprises of six 22-m diameter antennas and has a 3 km east-west track and a 214 m north-south spur. Five antennas are movable, while the sixth antenna is fixed at the 3 km western end of the tracks, allowing antennas to be set at several configurations, creating maximum and minimum baselines of 6 km and 30 m (Wilson et al. (2011) and ATCA users guide 1).

ATCA was upgraded with a compact array broad-band backend (CABB), which is a system designed to increase the observational capabilities of ATCA, with a bandwidth increase from 128 to 2048 MHz. This 16-fold increase made ATCA more versatile and powerful in its observations.

3.3 Source selection

The sources used in this study are samples of the CORNISH survey (Hoare et al. 2012), which is an arcsecond resolution radio continuum survey of the inner Galactic plane. The CORNISH survey consists of two parts, CORNISH-North and South. The CORNISH-North used the Very Large Array (VLA) to observe the northern hemisphere at 5 GHz, and CORNISH-South used ATCA to observe the southern hemisphere at 5 and 9 GHz. In this study, we use data from the CORNISH-South survey.

We were given 11 UCHII sources, in Table 3.1, based on their high integrated (radio) flux densities ($\geq 0.1$ Jy) found in Red MSX Survey (RMS) Urquhart et al. (2007). Only nine of eleven source were observed in RMS. In Table 3.1, column 1 is their galactic name as given by Urquhart et al.

Table 3.1: List of the eleven samples of UCHII regions from CORNISH-South. Nine sources were also observed in the Red MSX Survey (Urquhart et al. 2007) and their integrated flux densities are given.

<table>
<thead>
<tr>
<th>Source name</th>
<th>Source position</th>
<th>Int. flux density</th>
<th>Adopted distance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\alpha$(J2000)</td>
<td>$\delta$(J2000)</td>
<td>6 cm</td>
</tr>
<tr>
<td></td>
<td>(h m s)</td>
<td>($^\circ$ $'$ $''$)</td>
<td>(mJy)</td>
</tr>
<tr>
<td>G308.9176+00.1231B</td>
<td>13:43:01.74</td>
<td>-62:08:55.8</td>
<td>247.4</td>
</tr>
<tr>
<td>G324.1997+00.1192</td>
<td>15:32:53.21</td>
<td>-55:56:11.8</td>
<td>1192.0</td>
</tr>
<tr>
<td>G326.4719-00.3777</td>
<td>15:47:49.00</td>
<td>-54:58:33.0</td>
<td>342.5</td>
</tr>
<tr>
<td>G328.8074+00.6324</td>
<td>15:55:48.36</td>
<td>-52:43:06.8</td>
<td>–</td>
</tr>
<tr>
<td>G329.4720+00.2143</td>
<td>15:55:48.36</td>
<td>-52:43:06.8</td>
<td>–</td>
</tr>
<tr>
<td>G331.5414-00.0675</td>
<td>16:12:09.02</td>
<td>-51:25:47.7</td>
<td>75.0</td>
</tr>
<tr>
<td>G332.2944-00.0962</td>
<td>16:15:45.83</td>
<td>-50:56:02.4</td>
<td>175.6</td>
</tr>
<tr>
<td>G343.5024-00.0145</td>
<td>16:59:20.78</td>
<td>-42:32:37.5</td>
<td>176.9</td>
</tr>
<tr>
<td>G344.4257-00.0451A</td>
<td>17:02:09.35</td>
<td>-41:46:44.3</td>
<td>2139.0</td>
</tr>
<tr>
<td>G345.4881+00.3148</td>
<td>17:04:28.03</td>
<td>-40:46:23.3</td>
<td>1980.0</td>
</tr>
</tbody>
</table>
(2007), column 2-3 is their source positions which correspond to 6 cm source position from (table 5 of Urquhart et al. 2007), and column 4 is the integrated flux densities. G328.8074+00.6324 and G340.0543-00.2437 were not detected by Urquhart et al. (2007). In column 5 is the distances adopted from the RMS database 2, and all distances are the kinematic distances except for G332.2944-00.0962 which is from a spectrophotometric distance.

3.4 Observations and reduction

The observations were made from December 2010 to January 2012 by Dr. MG Hoare using ATCA with a receiver which covers 4 - 10 GHz range. ATCA can simultaneously observe radio continuum and radio recombination line emission, which is the case for these observations. The RRLs observed were H87α and H112α at rest frequency 9816.860 MHz and 4618.786 MHz, respectively. The continuum observations were at 3.6 cm (9 GHz) and 6 cm (5 GHz) wavelengths. The total bandwidth for this observation was 4.5 MHz, which is divided into 7000 - 9000 channels for line observations. The spectral resolution was 0.488 kHz. Table 3.2 summarizes the instrumental parameters. Table 3.3 summarizes the observation log. For each source (or UCHII region), column 1, one or more point sources (column 2) were observed, and we give their positions in columns 3 - 4. The date and time for each observation are in columns 5 - 6. The total integration time for each source was ∼10 hours.

The raw data of the sources in Table 3.3 had already been calibrated by Dr. M.G Hoare (private email communication) and the calibrators used are given in Table 3.4. We reduced the data using the Common Astronomy Software Application (CASA), where the cell size of 0.4′′, the image size of 1024 × 1024, the weighting set to Briggs, and the primary correction was done. When the signal-to-noise (SNR) of the continuum image was above 20, self-calibration was applied, and we carried out three iterations of phase calibration out. Once a continuum image was obtained we performed spectral line reduction averaging channels by 3 km/s ( ∼316 channels) to lower their computing time. The 3 km/s was chosen because RRLs have typical line width of ∼20 km/s (Kim & Koo 2001).

Table 3.2: Summary of instrumental parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>3.6 cm</th>
<th>6 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest frequency (MHz)</td>
<td>9816</td>
<td>4618</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Primary beam</td>
<td>5′.5</td>
<td>9′.9</td>
</tr>
<tr>
<td>Synthesized beam</td>
<td>∼1″.3</td>
<td>∼2″.5</td>
</tr>
<tr>
<td>Integration time (mins)</td>
<td>∼600</td>
<td>∼600</td>
</tr>
<tr>
<td>Theoretical rms (mJy beam⁻¹)</td>
<td>14</td>
<td>15</td>
</tr>
</tbody>
</table>

2http://rms.leeds.ac.uk
### Table 3.3: Observation log

<table>
<thead>
<tr>
<th>Source name</th>
<th>Position</th>
<th>Date start</th>
<th>Date end</th>
</tr>
</thead>
<tbody>
<tr>
<td>G308.9176+00.1231B</td>
<td>15:44:36.26 -62:07:30.1</td>
<td>02/01/2012/14:58:24.9</td>
<td>03/01/2012/01:07:14.9</td>
</tr>
<tr>
<td>G324.1997+00.1192</td>
<td>15:33:27.05 -55:56:29.7</td>
<td>05/01/2011/17:26:54.9</td>
<td>06/01/2011/03:36:54.9</td>
</tr>
<tr>
<td>G326.4719-00.3777</td>
<td>15:47:56.46 -54:56:34.5</td>
<td>02/01/2011/18:03:34.9</td>
<td>03/01/2011/04:44:34.9</td>
</tr>
<tr>
<td>G329.4720+00.2143</td>
<td>15:16:50.77 -52:41:41.5</td>
<td>01/01/2011/18:17:34.9</td>
<td>01/01/2011/24:54:24.9</td>
</tr>
<tr>
<td>G331.5414-00.0675</td>
<td>15:55:16.48 -52:42:54.7</td>
<td>01/01/2011/18:25:54.9</td>
<td>02/01/2011/05:34:34.9</td>
</tr>
</tbody>
</table>

### Table 3.4: The calibrators used to calibrate the source.

<table>
<thead>
<tr>
<th>Name</th>
<th>Flux (Jy)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3.6 cm</td>
</tr>
<tr>
<td>Primary flux calibrator, 1934-638</td>
<td>2.42</td>
</tr>
<tr>
<td>Secondary flux calibrator, 0823-500</td>
<td>1.44</td>
</tr>
<tr>
<td>Phase calibrators:</td>
<td></td>
</tr>
<tr>
<td>1352-63</td>
<td>1.07</td>
</tr>
<tr>
<td>1511-55</td>
<td>1.81</td>
</tr>
<tr>
<td>1640-50</td>
<td>0.85</td>
</tr>
<tr>
<td>1729-37</td>
<td>1.51</td>
</tr>
</tbody>
</table>

Note: Flux calibrator used was 1934-638 and the Amplitude calibrator was 0823-500. The flux and amplitude calibrator was the same for all the fields.
Chapter 4

Results

In this chapter, we present the results for the continuum maps that was produced for sources at 6 and 3.6 cm. We also present the emission over the full bandwidth of the sources detected at 6 cm to show any radio recombination line emission.

4.1 Continuum results

4.1.1 Continuum emission

Figure 4.1 and 4.2, at the end of this chapter, shows the contour maps from the continuum emission detected. In each map, the field of view is $40 \times 40$ arcsec$^2$. The source name and wavelength are given at the top of each image and the synthesized beam is given to the scale at the bottom left-hand corner.

From eleven sources that was observed, see Table 3.1, continuum emission was detected in nine of the sources at 6 cm and in four of the sources at 3.6 cm. Table 4.1 present their observed parameters. Their coordinates are given in columns 1 - 4, with the Galactic names obtained from Urquhart et al. (2007). The morphology of the source, in column 5, were obtained by following Wood & Churchwell (1989) schematic diagram. The angular sizes, in column 6 - 7, were obtained from fitting a two dimensional (2D)-Gaussian to the entire source. That is, the polynomial line was connected at the last contour level in each map and a 2D-Gaussian was fitted using CASA. The equatorial position in columns 3 - 4 we obtained from the fit. So is the peak flux densities, integrated flux densities and the full width half maximum (FWHM) of the synthesized beam, in columns 8, 9, 10 - 11, respectively. The image rms (noise) is given in column 12. The calibrators flux densities are not mentioned becasue the calibration had already been done by Dr. MG Hoare and the observation of the calibration was not available to us.
Table 4.1: Observe continuum parameters.

<table>
<thead>
<tr>
<th>Galactic Coordinates</th>
<th>Equatorial (J2000)</th>
<th>Morph.*</th>
<th>Angular size</th>
<th>Peak Int.</th>
<th>FWHM RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>α (h m s)</td>
<td>δ (° ′ ″)</td>
<td>max (arcsec)</td>
<td>min (mJy/beam)</td>
<td>max (mJy)</td>
</tr>
<tr>
<td>6 cm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G308.9176+00.1231B</td>
<td>13:43:01.8</td>
<td>-62:08:56.3</td>
<td>S</td>
<td>7.72</td>
<td>6.53</td>
</tr>
<tr>
<td>G324.1997+00.1192A</td>
<td>15:32:53.2</td>
<td>-55:56:10.8</td>
<td>C</td>
<td>7.53</td>
<td>5.86</td>
</tr>
<tr>
<td>G324.1997+00.1192B</td>
<td>13:43:01.8</td>
<td>-62:08:56.0</td>
<td>C</td>
<td>7.43</td>
<td>5.019</td>
</tr>
<tr>
<td>G344.4257-00.0451A</td>
<td>17:02:09.2</td>
<td>-41:46:44.3</td>
<td>U</td>
<td>4.92</td>
<td>4.51</td>
</tr>
<tr>
<td>G344.4257-00.0451C</td>
<td>17:04:28.1</td>
<td>-40:46:23.9</td>
<td>C</td>
<td>7.27</td>
<td>5.96</td>
</tr>
</tbody>
</table>

* The morphologies of the UCHII regions are denoted by Cometary (C), Spherical (S) and Unresolved (U), Core-halo (CH), and Shell (SH). The morphological classification was done through inspection by eye and is therefore rather subjective.

4.1.2 Physical parameters

As discussed by Wood & Churchwell (1989) and Kurtz et al. (1994) there are two approaches to derive the physical parameters which depend on the morphology of the source. First, the physical parameters for the spherical or unresolved sources only, are derived using the observed integrated flux densities. And for all the other sources except the irregular or multiple-peaked sources, the physical parameters are estimated using the peak flux densities per beam. The irregular or multiple-peaked sources are excluded because they have complicated structures for simple models to work.

4.1.2.1 Derived parameters for spherical sources

Table 4.2 present the derived physical parameters for the spherical sources using expressions from Panagia & Walmsley (1978). This approach assume that the sources are spherically symmetric, optically thin, homogeneous and ionization-bounded regions (Mezger & Henderson 1967; Panagia & Walmsley 1978; Wood & Churchwell 1989; Kurtz et al. 1994). The equations used to derive parameters shown in Table 4.2 are given below, using observed parameters of G308.9176+00.1231B as given in Table 4.1 as an example:

1. The source linear diameter, in column 4, is approximated by

$$\frac{\Delta s}{\text{pc}} = 0.2909 \left( \frac{\theta_R}{\text{arcmin}} \right) \left( \frac{D}{\text{kpc}} \right),$$

(4.1)
### Table 4.2: Derived parameter for spherical UCHII.

<table>
<thead>
<tr>
<th>Galactic Name</th>
<th>Linear Diameter of Sphere (pc)</th>
<th>n_e/10^4 (cm^{-3})</th>
<th>EM/10^7 (pc cm^{-6})</th>
<th>M(HII)/10^{-3} (M_☉)</th>
<th>τ_ν (pc cm^{-2})</th>
<th>U (pc cm^{-2})</th>
<th>Log N'_c (s^{-1})</th>
<th>Spectral Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>G308.9176+00.1231B</td>
<td>5.3</td>
<td>0.17</td>
<td>0.20</td>
<td>0.10</td>
<td>987</td>
<td>0.013</td>
<td>27.61</td>
<td>47.8</td>
</tr>
<tr>
<td>G324.1997+00.1192</td>
<td>6.8</td>
<td>0.11</td>
<td>0.53</td>
<td>0.47</td>
<td>714</td>
<td>0.062</td>
<td>34.35</td>
<td>48.1</td>
</tr>
<tr>
<td>G326.4719-00.3777</td>
<td>3.4</td>
<td>0.060</td>
<td>0.61</td>
<td>0.34</td>
<td>128</td>
<td>0.044</td>
<td>20.33</td>
<td>47.4</td>
</tr>
<tr>
<td>G329.4720+00.2143</td>
<td>7.2</td>
<td>0.18</td>
<td>0.21</td>
<td>0.13</td>
<td>1263</td>
<td>0.017</td>
<td>30.86</td>
<td>47.9</td>
</tr>
<tr>
<td>G340.0543-00.2437</td>
<td>3.1</td>
<td>0.078</td>
<td>0.41</td>
<td>0.19</td>
<td>185</td>
<td>0.026</td>
<td>20.14</td>
<td>47.4</td>
</tr>
</tbody>
</table>

where \( D \) is the distance to the source and \( \theta_R \) is the angular radius. It accounts for the difference between the model sphere diameter and observed FWHP of the source. Panagia & Walmsley (1978) (Table 1) gives the ratio of the angular radius (\( \theta_R \)) to the geometric diameter (\( \theta_G = \sqrt{\theta_{\text{min}} \times \theta_{\text{max}}} \)) and \( \theta_R = 0.950 \times \theta_G_{\text{arcmin}} \).

The source linear diameter can also be written as

\[
\frac{\Delta s}{\text{pc}} = 4.848 \times 10^{-3} \left( \frac{D}{\text{kpc}} \right) \left( \frac{\theta_G}{\text{arcsec}} \right)
\]

therefore

\[
\Delta s = (4.848 \times 10^{-3})(5.3)(7.0) = 0.18 \text{ pc.}
\]

2. The average electron density, column 5, is given by

\[
n_e = 3.113 \times 10^2 C_1 \left[ \frac{S_\nu}{\text{Jy}} \right]^{0.5} \left[ \frac{T}{10^4 \text{K}} \right]^{0.25} \left( \frac{D}{\text{kpc}} \right)^{-0.5} b(\nu, T)^{-0.5} \theta_R^{-1.5}
\]

where

\[
b(\nu, T) = 1 + 0.3195\log(T/10^4 \text{K}) - 0.2130\log(\nu/1\text{GHz})
\]

therefore

\[
n_e = (3.113 \times 10^2)((271 \times 10^3)^{0.5})((10^4/10^4)^{0.25})(5.3^{-0.5})(0.858^{-0.5})(0.112^{-1.5}) = 2.0 \times 10^3 \text{ cm}^{-3}.
\]

Note: \( S_\nu \) is the observed integrated flux density given in Table 4.1 and \( \nu \) is the observing frequency.

3. The emission measure, in column 6, is calculated as follows

\[
\frac{EM}{\text{pc cm}^{-6}} = 5.638 \times 10^4 C_2 \left[ \frac{S_\nu}{\text{Jy}} \right] \left[ \frac{T}{10^4 \text{K}} \right] b(\nu, T)\theta_R^{-2}
\]
then
\[
EM = (5.638 \times 10^4)(271 \times 10^{-3})(10^4/10^4)(0.858)(0.112^{-2})
= 1.0 \times 10^7 \text{ pc cm}^{-6}.
\]

4. In column 7 is the total mass of the HII region and is given by
\[
\frac{M}{M_\odot} = 0.7934C_3 \left[ \frac{S_\nu}{\text{Jy}} \right]^{0.5} \left[ \frac{T}{10^4 \text{K}} \right]^{0.25} \left[ \frac{D}{\text{kpc}} \right]^{2.5} b(\nu, T)^{-0.5} \theta_R^4 (1 + Y)^{-1} \tag{4.4}
\]

\[
Y = \frac{N(\text{He}^+)}{N(\text{H}^+)} \text{ and is assumed to be } 0.1 \text{ (Wood & Churchwell 1989).}
\]

\[
M = (0.7934)((271 \times 10^{-3})^{0.5})((10^4/10^4)^{0.25})(5.32^{2.5})(0.858^{-0.5})(0.112^{1.5})(1 + 0.1)^{-1}
= 1.0M_\odot.
\]

5. The optical depth (column 8) expression is from Oster (1961) as presented by Mezger & Henderson (1967) as
\[
\tau_C = 3.014 \times 10^{-2} \left[ \frac{T_e}{K} \right]^{-1.5} \left[ \frac{\nu}{\text{GHz}} \right]^{-2.0} \left\{ \ln \left[ 4.955 \times 10^{-2} \left( \frac{\nu}{\text{GHz}} \right)^{-1} \right] + 1.5 \ln \left( \frac{T_e}{K} \right) \right\} \left( \frac{EM}{\text{pc cm}^{-6}} \right) \tag{4.5}
\]
then
\[
\tau_C = (3.014 \times 10^{-2})((10^4)^{-1.5})(4.618^{-2.0})(\ln((4.955 \times 10^{-2})(4.618^{-1})) + 1.5 \ln(10^4)) \times 1037874 \times 10^7
= 0.013.
\]

6. Panagia (1973) estimated the spectral type of the star which emits the Lyman continuum photons flux required to maintain the ionized region by calculating the excitation parameter, in column 9, as
\[
\left( \frac{U}{\text{pc cm}^{-2}} \right) = 4.5526 \left( a^{-1} \left( \frac{\nu}{\text{GHz}} \right)^{0.1} \left( \frac{T_e}{K} \right)^{0.35} \left( \frac{S_\nu}{\text{Jy}} \right) \left( \frac{D}{\text{kpc}} \right)^2 \right)^{1/3} \tag{4.6}
\]
then
\[
U = 4.5526((4.618^{0.1})(10^4)^{0.35})(271 \times 10^{-3})(5.3^2) \times 10^7
= 27.61 \text{ pc cm}^{-2}.
\]

where \( a \) is a ratio of continuum optical depth by Oster (1961) to the approximate optical depth by Altenhoff et al. (1960). However, \( a \) is usually given as unity (Mezger & Henderson 1967).

7. The Lyman-continuum photon flux, in column 10, is
\[
N_c \geq 8.04 \times 10^{46} T_e^{-0.85} U^3 \tag{4.7}
\]
Table 4.3: Derived parameters for other UCHII regions

<table>
<thead>
<tr>
<th>Name</th>
<th>$D_{\odot}$ (kpc)</th>
<th>$\Delta s$ (pc)</th>
<th>$T_b$ (K)</th>
<th>$\tau_{\nu}$ (pc cm$^{-6}$)</th>
<th>$EM/10^7$ (cm$^{-3}$)</th>
<th>$n_e/10^4$ (cm$^{-3}$)</th>
<th>$U$ (pc cm$^{-2}$)</th>
<th>Log $N'_c$ (s$^{-1}$)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>G324.1997+00.1192 A</td>
<td>6.8</td>
<td>0.081</td>
<td>2007</td>
<td>0.22</td>
<td>1.69</td>
<td>1.43</td>
<td>51.7</td>
<td>48.7</td>
<td>O7</td>
</tr>
<tr>
<td>G328.8074+00.6324</td>
<td>2.8</td>
<td>0.037</td>
<td>1273</td>
<td>0.13</td>
<td>1.03</td>
<td>1.65</td>
<td>25.71</td>
<td>47.7</td>
<td>O9.5</td>
</tr>
<tr>
<td>G343.5024-00.0145</td>
<td>2.7</td>
<td>0.039</td>
<td>294</td>
<td>0.029</td>
<td>0.22</td>
<td>0.75</td>
<td>18.3</td>
<td>47.3</td>
<td>B0</td>
</tr>
<tr>
<td>G344.4257-00.0451A</td>
<td>4.7</td>
<td>0.067</td>
<td>1886</td>
<td>0.20</td>
<td>1.58</td>
<td>1.53</td>
<td>52.8</td>
<td>48.7</td>
<td>O7</td>
</tr>
<tr>
<td>G345.4881+00.3148</td>
<td>2.1</td>
<td>0.024</td>
<td>3889</td>
<td>0.49</td>
<td>3.73</td>
<td>3.93</td>
<td>26.5</td>
<td>47.8</td>
<td>O7</td>
</tr>
</tbody>
</table>

\[ N_c \geq (8.04 \times 10^{46})((10^4)^{-0.85})(27.61^3) \geq 6.73 \times 10^{47} \text{s}^{-1}. \]

$C_1$, $C_2$ and $C_3$ in Equations 4.2, 4.3 and 4.4, respectively, are model constants assuming homogeneous sphere (Panagia & Walmsley 1978). These constants are usually unity.

4.1.2.2 Derived parameters for non-spherical regions

Non-spherical regions include cometary, core-halo and shell, and according to Wood & Churchwell (1989) and Kurtz et al. (1994) to derive the physical parameters for these regions it requires a three-dimensional structure and integrates over the volume of the source. However, this model requires parameters that are not known. Hence, to avoid this difficulty, the physical parameters are estimated using the peak flux density of the source in the synthesized beam. Table 4.3 show the derived parameters using the equations below. G324.1997+00.1192 A is used as an example.

The source diameter $\Delta s$ (or the area of the emission) given column 4 is derived similarly to Equation 4.1. Also the excitation parameter, in column 9, and Lyman continuum photon flux in column 10, uses the same equations as Equations 4.6 and 4.7, respectively. Their derivations will not be shown here.

1. The synthesized beam brightness temperature of the source is given in column 5 as

\[ T_b = \frac{S_\nu 10^{-29} c^2}{2 \nu^2 k \Omega_b} \]  

where

- $S_\nu$ is the peak flux density (mJy/beam).
- $\nu$ is the observing frequency in units of Hz.
• $\Omega_b$ is the solid angle of the synthesized beam and is given by

$$\left( \frac{\Omega_b}{\text{rad}} \right) = 1.133 (O_{\text{min}} \times O_{\text{max}}).$$

Therefore

$$T_b = \frac{(186 \times 10^{-29})(2.99 \times 10^8)^2}{2((4.619 \times 10^9)^2)(1.407 \times 10^{-10})} = 2007 \text{ K.}$$

Assuming the beam is uniformly filled with the ionized gas the electron temperature $T_e$ is assumed to be $10^4 \text{ K}$.

2. In column 7 is the optical depth estimated from the relation of the brightness temperature and electron temperature (Wilson et al. 2009), i.e.

$$T_b = T_e (1 - e^\tau),$$

then

$$\tau = -\ln \left(1 - \frac{T_b}{T_e}\right)$$

$$= -\ln \left(1 - \frac{2007}{10^4}\right)$$

$$= 0.22$$

assuming that the beam is uniformly filled with $T_e \sim 10^4 \text{ K}$ ionized gas.

3. The emission measure is given in column 8. Its expression is from Mezger & Henderson (1967) and it used the optical optical (Equation 4.9) of the free-free emission.

$$\frac{\text{EM}}{\text{pc cm}^{-6}} = \frac{\tau}{8.235 \times 10^{-2} a T_e^{-1.35} \nu^{-2.1}}$$

then

$$EM = \frac{\tau}{(8.235 \times 10^{-2})(10^4)^{-1.35}(4.618^{-2.1})}$$

$$= 1.7 \times 10^7 \text{ pc cm}^{-6}$$

where $\nu$ is in units of GHz.

4. The electron density, in column 9, is given as

$$n_e = \sqrt{\frac{\text{EM}}{\Delta s}}$$
then

\[
    n_e = \sqrt{\frac{1.7 \times 10^7}{0.081}} = 2.6 \times 10^4 \text{ cm}^{-3}.
\]

### 4.2 Line emission results

Figure 4.3 show the plots of the emission for detected UCHII regions at 6 cm only, because the continuum emission for detected at 3.6 cm is too weak to assume the detectability of the RRLs. Hence, their emission are not shown here. For each source in Figure 4.3, the top emission over the velocity range is comprises of free-free (continuum) emission and line emission. We found that sources that were observed in Red MSX Survey\(^1\) (Urquhart et al. 2007) also have associated maser emission. The vertical dashed lines in Figure 4.3 indicated the velocities of the associated maser emission. Since the emissions from the same medium have velocities that are almost the same, the velocity of the RRLs from our sources should almost be the same to the velocity of the maser emission. Hence, the RRL emission is expected to be, or it should be at least around ±5 km/s of the line. If the radio recombination line emission exists, its emission should be above the continuum emission by at least 3\(\sigma\) continuum dispersion. However, in all the spectra, it shows no radio recombination line emission. The 3rd order polynomial was fitted on the emission, only on the free-free emission. The free-free emission is taken to be all the emission around ±5 km/s of the vertical dashed line, within ±5 km/s the emission belongs to line emission. Subtracting off the fitted emission, the remaining emission belongs to the line emission. Its spectra are expected to show zero-emission everywhere except where there is radio recombination line emission. The radio recombination line emission should have emission that is at least 3\(\sigma\) which is where the horizontal dashed line is at the bottom spectra. No recombination line emission was visible in any of the observed sources.

\(^1\)http://rms.leeds.ac.uk/cgi-bin/public/RMS_CONE_SEARCH.cgi
Figure 4.1: Radio continuum emission of the observed UCHII regions at 6 cm, shown in contour maps. The synthesized beam is given to scale at the bottom left hand corner. The contours levels (mJy/beam) used for the different sources respectively are: G308.9176+00.1231B = [-12, -4, 6, 14, 23, 32, 41, 50, 59, 68, 77, 86], G324.1997+00.1192 = [30, 50, 70, 90, 110, 130, 150, 170, 190, 210, 230, 250], G326.4719-00.3777 = [30, 41, 51, 63, 74, 85, 96, 106, 117, 128, 139, 150], G328.8074+00.6324 = [50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160], G329.4720+00.2143 = [20, 23, 26, 28, 31, 34, 36, 39, 42, 45, 47, 50], G340.0543-00.2437 = [30, 35, 39, 44, 48, 53, 57, 62, 66, 71, 76, 80].
Figure 4.1: Continues. The contour levels (mJy/beam) for the different sources respectively are: G343.5024-00.0145 = [20, 24, 27, 31, 35, 38, 42, 46, 49, 53, 56, 60], G344.4257-00.0451A = [50, 77, 105, 132, 159, 186, 214, 241, 268, 296, 323, 350], G345.4881+00.3148 = [35, 59, 83, 107, 131, 156, 180, 204, 227, 252, 276, 300].
Figure 4.2: Radio continuum emission of the observed UCHII regions at 3.6 cm, shown in contour maps. The synthesized beam is given to scale at the bottom left hand corner. The contour levels (mJy/beam) for the different sources respectively are: 

- **G308.9176+00.1231B** = [10, 12, 14, 16, 17, 19, 21, 23, 25, 26, 28, 30],
- **G324.1997+00.1192** = [30, 45, 60, 75, 90],
- **G344.4257+00.0451A** = [70, 77, 85, 92, 99, 106, 114, 121, 128, 136, 143, 150],
- **G345.4881+00.3148** = [100, 118, 136, 155, 173, 191, 209, 227, 246, 264, 282, 300].
Figure 4.3: This Figure shows the emission coming from the UCHII region. The top panel shows the emission over the velocity range from both continuum and line emission. The dotted vertical line indicates where the radio recombination line emission is expected to be. The bottom panel shows the emission when the continuum emission is subtracted. If the line emission is present it should be above the $3\sigma$ level, that the dotted horizontal line.
Figure 4.3: continue.
Figure 4.3: continue.
Figure 4.3: continue.
Figure 4.3: continue.
Chapter 5

Discussion and conclusion

5.1 Comparison of the peak and integrated flux densities with those of Urquhart et al. (2007)

Urquhart et al. (2007) conducted a high-resolution radio continuum survey in which they aimed to distinguish massive young stellar objects and embedded objects such as UCHII, evolved stars and planetary nebulae. They observed 896 sources at 3.6 and 6 cm (spatial resolution of about 1 - 3") using ATCA six km baseline with configuration either 6C or 6D. They used a bandwidth of 128 MHz for each frequency with frequency bands centered at 4800 and 8640 MHz. The total-on-source integration time was ten minutes. They calibrated and reduce their data using the MIRIAD reduction package. They found 199 sources with radio emission consistent with UCHII regions.

Nine of our observed sources (Table 3.1) were taken from the Urquhart et al. (2007) survey and was observed with ATCA at 3.6 and 6 cm with the aim to detect radio recombination line emission. The observations were done with a bandwidth of 4.5 MHz for each frequency with bands centered at 4600 and 9800 MHz. Table 5.1 show comparison between the sources angular sizes, peak and integrated flux densities as observed from this study with those observed by Urquhart et al. (2007). Columns 11 and 12 show the relative difference in percentages between peak fluxes and integrated fluxes. The relative difference is defined as

\[
\text{Relative difference} = \frac{S_u - S}{S} \times 100
\]

where \(S_u\) represent peak/integrated flux densities from Urquhart et al. (2007) and \(S\) represent the peak/integrated flux densities from this study. The negative percentage means that our observed fluxes are higher than those of Urquhart et al. (2007), and the positive percentage means the opposite. It is seen that the differences are large in both peak and integrated fluxes, their dispersions are 42.1 and 65.6 respectively. Because the data for this study was already calibrated and it was not possible to check to what extent these large differences might be due to the calibration.
Table 5.1: Comparing our study with those of Urquhart et al. (2007)

<table>
<thead>
<tr>
<th>Galactic</th>
<th>This study</th>
<th>Urquhart et al. (2007) study</th>
<th>Relative difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Angular size</td>
<td>Peak Sν</td>
<td>Int.</td>
</tr>
<tr>
<td></td>
<td>max (arcsec)</td>
<td>min (mJy/beam)</td>
<td>(mJy)</td>
</tr>
<tr>
<td>G308.9176+00.1231B</td>
<td>7.72</td>
<td>6.53</td>
<td>83</td>
</tr>
<tr>
<td>G324.1997+00.1192A</td>
<td>7.53</td>
<td>5.86</td>
<td>186</td>
</tr>
<tr>
<td>G326.4719-00.3777</td>
<td>4.09</td>
<td>3.14</td>
<td>186</td>
</tr>
<tr>
<td>G329.4720+00.2143</td>
<td>5.92</td>
<td>5.13</td>
<td>118</td>
</tr>
<tr>
<td>G343.5024-00.0145</td>
<td>8.91</td>
<td>7.67</td>
<td>40</td>
</tr>
<tr>
<td>G344.4257-00.0451A</td>
<td>11.03</td>
<td>9.61</td>
<td>248</td>
</tr>
<tr>
<td>G345.4881+00.3148</td>
<td>7.27</td>
<td>5.96</td>
<td>326</td>
</tr>
</tbody>
</table>

5.2 Evaluation of derived continuum parameters

Kurtz (2002) (Table 1.1) show the typical physical parameters as derived from known UCHII region from observation by, e.g. Wood & Churchwell (1989); Kurtz et al. (1994); Kim & Koo (2001) and Shabala et al. (2006).

The derived physical parameters (in Table 4.2 and 4.3) were compared with those derived by Wood & Churchwell (1989) and Kurtz et al. (1994). Wood & Churchwell (1989) observed 75 UCHII regions with 0.4" resolution at 2 and 6 cm using the VLA. They derived physical properties for 20 spherical and 45 non-spherical UCHII regions. Kurtz et al. (1994) also observed 75 compact radio sources using the VLA at 2 and 3.6 cm with resolution of ≤ 1". They derived physical parameters for 27 spherical and 30 non-spherical UCHII regions. Table 5.2 show their average parameters and dispersions (σ). We found that the linear diameters (Δs) (Table 4.2 and 4.3) are within 1σ of Wood & Churchwell (1989) and Kurtz et al. (1994) (see Table 5.2), except for G308.9176+00.1231B and G329.4720+00.2143 which are within 2σ. The derived electron densities (n_e) and emission measures (EM) are within 1σ, but the electron densities for spherical source (Table 4.2) are within 2σ of Wood & Churchwell (1989). We found that the derived total mass of spherical regions are higher than expected, they are above 3σ of both Wood & Churchwell (1989) and Kurtz et al. (1994).

Table 5.2: The average and dispersion derived physical properties for the UCHII regions from Wood & Churchwell (1989) and Kurtz et al. (1994).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spherical</td>
<td>Non-spherical</td>
</tr>
<tr>
<td></td>
<td>mean dispersion (σ)</td>
<td>mean dispersion (σ)</td>
</tr>
<tr>
<td>Δs (pc)</td>
<td>0.063</td>
<td>0.11</td>
</tr>
<tr>
<td>EM/10^7 (pc cm^-6)</td>
<td>7.68</td>
<td>9.9</td>
</tr>
<tr>
<td>n_e/10^4 (cm^-3)</td>
<td>7.2</td>
<td>6.3</td>
</tr>
<tr>
<td>U (pc cm^-2)</td>
<td>20.9</td>
<td>13.9</td>
</tr>
<tr>
<td>M(HII)/10^-3 (M⊙)</td>
<td>64.47</td>
<td>116.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We found that derived parameter for non-spherical regions (Table 4.3) are more closer to the “typical” parameters of the UCHII regions than the derive parameters for spherical regions (Table 4.2). Hence, we estimated the parameters for all the sources using the non-spherical model (see Table 4.3)
Table 5.3: Derived parameters if all UCHII regions are assumed to be nonspherical.

<table>
<thead>
<tr>
<th>Galactic Name</th>
<th>$D_v$ (kpc)</th>
<th>$\Delta s$ (pc)</th>
<th>$T_b$ (K)</th>
<th>$\tau_C$</th>
<th>EM/10$^7$ (pc cm$^{-6}$)</th>
<th>$n_e/10^3$ (cm$^{-3}$)</th>
<th>$U$ (pc cm$^{-2}$)</th>
<th>Log $N_e'$ (s$^{-1}$)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>G308.9176+00.1231B</td>
<td>5.3</td>
<td>0.068</td>
<td>776</td>
<td>0.08</td>
<td>0.61</td>
<td>0.94</td>
<td>27.61</td>
<td>47.8</td>
<td>O9.5</td>
</tr>
<tr>
<td>G324.1997+00.1192</td>
<td>A 6.8</td>
<td>0.081</td>
<td>2007</td>
<td>0.22</td>
<td>1.69</td>
<td>1.43</td>
<td>51.7</td>
<td>48.7</td>
<td>O7</td>
</tr>
<tr>
<td></td>
<td>B 6.8</td>
<td>0.081</td>
<td>2007</td>
<td>0.22</td>
<td>1.69</td>
<td>1.43</td>
<td>51.7</td>
<td>48.7</td>
<td>O7</td>
</tr>
<tr>
<td>G326.4719-00.3777</td>
<td>3.4</td>
<td>0.050</td>
<td>1188</td>
<td>0.12</td>
<td>0.95</td>
<td>1.37</td>
<td>20.33</td>
<td>47.4</td>
<td>B0</td>
</tr>
<tr>
<td>G328.8074+00.6324</td>
<td>2.8</td>
<td>0.037</td>
<td>1273</td>
<td>0.13</td>
<td>1.03</td>
<td>1.65</td>
<td>25.71</td>
<td>47.7</td>
<td>O9.5</td>
</tr>
<tr>
<td>G329.4720+00.2143</td>
<td>7.2</td>
<td>0.097</td>
<td>1001</td>
<td>0.10</td>
<td>0.79</td>
<td>0.90</td>
<td>30.86</td>
<td>47.9</td>
<td>O9</td>
</tr>
<tr>
<td>G340.0543-00.2437</td>
<td>3.1</td>
<td>0.040</td>
<td>707</td>
<td>0.07</td>
<td>0.55</td>
<td>1.17</td>
<td>20.14</td>
<td>47.4</td>
<td>B0</td>
</tr>
<tr>
<td>G343.5024-00.0145</td>
<td>2.7</td>
<td>0.039</td>
<td>294</td>
<td>0.03</td>
<td>0.22</td>
<td>0.75</td>
<td>18.3</td>
<td>47.3</td>
<td>B0</td>
</tr>
<tr>
<td>G344.4257-00.0451A</td>
<td>4.7</td>
<td>0.067</td>
<td>1886</td>
<td>0.20</td>
<td>1.58</td>
<td>1.53</td>
<td>52.8</td>
<td>48.7</td>
<td>O7</td>
</tr>
<tr>
<td>G345.4881+00.3148</td>
<td>2.1</td>
<td>0.024</td>
<td>3889</td>
<td>0.49</td>
<td>3.73</td>
<td>3.93</td>
<td>26.5</td>
<td>47.8</td>
<td>O7</td>
</tr>
</tbody>
</table>

5.3. Here we found that all the parameters are within 1σ of both Wood & Churchwell (1989) and Kurtz et al. (1994) (see Table 5.2).

5.3 The radio recombination line analysis

Radio recombination line emission is superimposed onto the free-free continuum emission. However, the radio recombination line emission is weaker when compared to continuum emissions (Roelfsema & Goss 1992). Sewilo et al. (2004) found that radio recombination line emission can be very low (< 0.04 mJy). It is advisable that to observe a good line emission, with high signal-to-noise, to integrate over the entire HII region.

Our study aims to search for radio recombination line emission in UCHII regions. These regions (Table 3.1) have not been previously observed for radio recombination line emissions. We found no recombination line emission in all the sources, see Figure 4.3. We found from the top panel in Figure 4.3 that the free-free emission is dominating.

5.3.1 Expected Line parameters

From the derived physical parameters in Table 4.2 of the free-free emission, we could make few assumptions to derive the line parameters. In section 2.3.3 and (13.6 of Wilson et al. 2009) it showed that to derived electron temperature ($T_e$) an HII regions has to be

1. homogeneous and isothermal,
2. the optical depth for both continuum ($\tau_C$) and line ($\tau_L$) must be small, i.e. $|\tau_L + \tau_C| \ll 1$.
3. then the line emission can be treated as if it were formed and transferred in LTE, where
departure coefficients are $b_n = 1$ and $\beta = 1$.

When all these conditions are met, the line-to-continuum ratio, Equation 2.29, can be solved for the
electron temperature ($T_e$). However, to derive the expected line parameter we have to assume both
the electron temperature $T_e$ and the line width $\Delta \nu$, and solve for line flux density.

Here we show how we derive the line parameters, we use G308.9176+00.1231B derived continuum
values in Table 4.2 as an example. However, all the sources follow the same method.

1. If we assume the region has $T_e \sim 10^4$ K and the line emission with line width $\Delta \nu \sim 10$ km s$^{-1}$,
the line parameters would have

- the line optical depth of

$$\tau_L = 1.92 \times 10^3 \left( \frac{T_e}{\text{K}} \right)^{-5/2} \left( \frac{\Delta \nu}{\text{kHz}} \right)^{-1} \left( \frac{E M}{\text{pc cm}^{-6}} \right)$$

$$= (1.92 \times 10^3)(10^4)^{-5/2}(167)^{-1}(10^6)$$

$$= 1.1 \times 10^{-3}.$$  \hspace{1cm} (5.1)

the continuum optical depth is $\tau_C = 0.013 \ll 1$, meaning $|\tau_C + \tau_L| \ll 1$.

- Thus, the line flux density is estimated by

$$S_L = \left[ 6.985 \times 10^3 \left( \frac{\nu}{\text{GHz}} \right)^{1.1} \left( \frac{T_e}{\text{K}} \right)^{-1.15} \left( \frac{\Delta \nu}{\text{km s}^{-1}} \right)^{-1} \frac{1}{1 + \frac{N(H_e)}{N(H^+)}} \right] S_C$$

$$= ((6.985 \times 10^3)(4.619)^{1.1}(10^4)^{-1.15}(10)^{-1}(1/(1 + 0.1))) \times 271$$

$$= 23 \text{ mJy}.$$  \hspace{1cm} (5.2)

In Figure 4.3 we showed that the line emission needs to be above $3\sigma$ level (where $\sigma$ is the
dispersion of the continuum emission) to be visible and detectable. However, we detected
no line emissions, that means the line emission has the flux density that is below the $3\sigma$
level.

For this region, with $T_e = 10^4$ K and the line width $\Delta \nu = 10$ km s$^{-1}$, we see that line
emission would have the flux density of $S_L = 22$ mJy which is above the $3\sigma$ level. Hence,
these regions could not be the region we observe.

2. If we now assume that the region has $T_e \sim 8000$ K and $\Delta \nu \sim 10$ km s$^{-1}$, the line parameters
would have

- the line optical depth of
\[ \tau_L = (1.92 \times 10^3)(8000)^{-5/2}(167)^{-1}(10^6) \]
\[ = 2.0 \times 10^{-3}. \] (5.3)

- The line flux density would be

\[ S_L = ((6.985 \times 10^3)(4.619)^{1.1}(8000)^{-1.15}(10)^{-1}(1/(1 + 0.1))) \times 271 \]
\[ = 29 \text{ mJy}. \] (5.4)

The line flux density is also above the 3\( \sigma \) level. Thus, these conditions are not for our observed region.

3. We then assume the region has \( T_e \sim 12000 \text{ K} \) and \( \Delta \nu \sim 10 \text{ km s}^{-1} \), the line parameters would be

- the line optical depth of

\[ \tau_L = (1.92 \times 10^3)(12000)^{-5/2}(167)^{-1}(10^6) \]
\[ = 7.2 \times 10^{-4}. \] (5.5)

- and the line flux density is

\[ S_L = ((6.985 \times 10^3)(4.619)^{1.1}(12000)^{-1.15}(10)^{-1}(1/(1 + 0.1))) \times 271 \]
\[ = 18 \text{ mJy}. \] (5.6)

Here we see that the line flux density is slightly above the 3\( \sigma \) level.

4. If the region is assumed to have the \( T_e \sim 10^4 \text{ K} \) and \( \Delta \nu \sim 25 \text{ km s}^{-1} \), the line parameters would be

- the line optical depth of

\[ \tau_L = (1.92 \times 10^3)(10^4)^{-5/2}(416)^{-1}(10^6) \]
\[ = 4.6 \times 10^{-4}. \] (5.7)

- The line flux density is

\[ S_L = ((6.985 \times 10^3)(4.619)^{1.1}(10^4)^{-1.15}(10)^{-1}(1/(1 + 0.1))) \times 271 \]
\[ = 9 \text{ mJy}. \] (5.8)
The line flux density is below the $3\sigma$ level, which means the line emission would not be visible. These conditions fit what we found in Figure 4.3, meaning that the line emission probably has the width that is broader than 15 km s$^{-1}$.

The above calculations shows that different assumptions results in different line flux densities. Hence, in Figure 5.1 we show the plots of line flux densities ($S_L$) against the line width ($\Delta \nu$) and the electron temperature ($T_e$) when $T_e$ and $\Delta \nu$ are constant, respectively. The line flux densities are plotted with different continuum flux densities ($S_C$) starting from integrated flux density ($S_{int}$) down to 30% of $S_{int}$, keeping emission measure ($EM$) constant as given in Table 4.2 for all the areas.

If the region is assumed to have the electron temperature $T_e = 10^4$ K (Figure 5.1 top left), the line emission with the line width above 25 km s$^{-1}$ would not be detectable. Only if the line width is below 25 km s$^{-1}$ and integrating over the entire region ($S_{int}$) would the line emission be detectable. The bottom left plot show that, if the region is assumed to have the electron temperature $T_e = 12000$ K, the only line emission detectable is from the line emission with line width $< 15$ km s$^{-1}$ and integrated over the entire region.

If we assume that the line emission exist in a region and has the line width $\Delta \nu = 10$ km s$^{-1}$ (top right in Figure 5.1), we see from the plot that the line emission would be detectable if the region have electron temperature ranging from $6000 < T_e < 13000$ K if we integrate over the entire region ($S_{int}$). However, if the line width is assume to be 25 km s$^{-1}$ (bottom right in Figure 5.1), the line emission is only detectable if the region have the electron temperature $T_e < 7000$ K.

For our study, we did not detect any line emissions, and from Figure 5.1 we can infer that our regions either have: 1) $T_e = 10^4$ or 12000 K and the line emission with width $\Delta \nu > 25$ km s$^{-1}$; or 2) $T_e > 13000$ K and the line width $\Delta \nu = 10$ km s$^{-1}$; or 3) $T_e > 8000$ K and the line width $\Delta \nu = 25$ km s$^{-1}$.

### 5.4 Conclusion

RRLs are a powerful tool for astrophysical research (Roelfsema & Goss 1992; Kim & Koo 2001; Sewilo et al. 2004). They can provide accurate information about their origin and environments.

In our study we aimed to search for a radio recombination line in UCHII regions. The data used is part of the CORNISH-South survey which used ATCA to conduct an unbiased survey for UCHII regions which will help in the study of high-mass star formation. The CORNISH is designed to simultaneously observe radio continuum and the RRL. Hence, for our study we aim to search for radio recombination line emission towards eleven UCHII regions in 5 and 9 GHz. The raw data provided had already been calibrated by Dr. M.G Hoare. The data was reduced and analysed using CASA.
In eleven sources, we found nine sources in 5 GHz with free-free emission. And only four sources in 9 GHz. The observed flux densities (peak and integrated) of seven sources in 5 GHz were compared with flux densities obtained by Urquhart et al. (2007) and we found that fluxes are significantly different. One of the reasons for the differences could be due to the calibration. We derived the physical parameters for the detected sources only at 5 GHz and found that their parameters are mostly within 2σ of Wood & Churchwell (1989) and Kurtz et al. (1994).

In all detected sources, we found no radio recombination line emission. Hence, we derive the expected line parameters. We found that the recombination line emission that could exist in these regions could have line widths greater than 25 km s⁻¹, given the regions have electron temperature \( T_e > 8000 \) K. Such line emission can exist in these regions, but have low emission which is significantly obscured by the free-free emission. The radio recombination line from UCHII regions are known to have widths
between 10 - 30 km/s, however, Sewilo et al. (2004) found radio recombination lines for HCHII regions with widths ranging from 30 - 162 km s$^{-1}$ and emission as low as < 0.04 mJy.

It is possible that our observed sources are in their early stages of UCHII regions, and they have radio recombination line emission with broader line widths ($\Delta \nu > 25$ km s$^{-1}$) than expected. And also their line intensity could be very low as well.
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