



**Searching for Compact Optically
Thick Hypercompact HII Regions
SCOTCH**

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ABSTRACT

Hypercompact HII regions (HC HII) trace one of the earliest observable ionised stages of massive star formation, marking the point at which a newly formed massive star begins to ionise its surrounding material. Their small sizes, high densities, short lifetimes, and large optical depths make them difficult to detect, leaving their properties poorly represented in the literature. Since HC HII regions often remain optically thick below ~ 20 GHz, they are commonly missed in radio surveys of HII regions, which are typically conducted at frequencies of ~ 5 GHz. Increasing the known sample of HC HII regions is therefore essential for understanding when ionisation begins, how compact HII regions evolve, and how feedback develops during the embedded stages of massive-star formation. This thesis addresses these questions through the Search for Clandestine Optically Thick Compact HII Regions (SCOTCH), a systematic high-frequency radio continuum survey towards methanol maser sites, which are themselves well-established signposts of young, deeply embedded high-mass protostars.

Targeted high-frequency radio continuum observations at 18–24 GHz were used to investigate 476 methanol maser sites from the Methanol Multibeam survey. Observations were carried out for 355 sources using the Australia Telescope Compact Array, these were supplemented by archival high-frequency data for a further 121 sources. Across the survey, 189 compact radio sources were detected. Cross-matching with mid-infrared, submillimetre dust continuum, and lower-frequency radio data identified 134 compact sources associated with both methanol masers and dense molecular material. These sources are identified as embedded compact HII region candidates tracing early stages of massive-star formation. Candidate HC HII regions were selected based

on compact morphology, positional association with methanol masers, and rising or optically thick radio spectra between 5 and 18 GHz. A total of 81 candidates were followed up at higher angular resolution at 18 and 24 GHz.

The final SCOTCH sample contains 61 compact ionised sources, including 34 HC HII regions, 15 intermediate objects, 9 UC HII regions, and 3 jet-like candidates. Of these, 48 are newly identified HC HII regions or intermediate objects, increasing the known sample by a factor of approximately three. Several sources remain optically thick even at 24 GHz, indicating that they are among the youngest and densest compact ionised regions in the sample, and that some derived physical properties remain lower limits. The newly identified sources are typically smaller, denser, and associated with lower-luminosity early B-type stars than many previously known HC HII regions. This demonstrates that compact, optically thick ionised regions are more common than previously recognised and are not limited to the most luminous O-type stars.

The enlarged SCOTCH sample shows that HC HII and UC HII regions form a continuous evolutionary sequence rather than two clearly distinct physical classes. Their physical properties change smoothly from small, dense, optically thick HC HII regions to larger, more evolved UC HII regions, with transition objects bridging the two stages. The HC/UC distinction therefore remains useful as an observational classification, but should not necessarily be interpreted as evidence for separate physical populations. These results support a picture in which ionisation begins while massive young stars remain deeply embedded, and where accretion, ionisation, and feedback can co-exist during the early evolution of massive stars. The detection rate of HC HII regions and transition objects is approximately ten per cent, demonstrating that methanol maser selection combined with high-frequency radio continuum observations provides an efficient route to finding the youngest compact ionised regions. Extending SCOTCH to the remaining northern methanol maser population would provide a more complete Galactic census of HC HII regions and stronger constraints on their lifetimes, luminosity distribution, and evolutionary behaviour.

DECLARATIONS

The content of this thesis is the original work of the author and has not been submitted to any other institution or for any other degree.

Chapters 3, 4, and 5 have been adapted and expanded from research published as Patel et al. (2023), Patel et al. (2024) and Patel et al. (2025).

All work presented is the author's own unless otherwise stated, and all references to external work have been appropriately cited.

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CHAPTER 1

INTRODUCTION

The birth and early evolution of massive stars ($> 8 M_{\odot}$) have been widely studied over the past few decades, yet a complete evolutionary sequence remains unknown due to the challenges in observing these objects. Throughout their lifetimes, massive stars profoundly impact their surroundings through mechanisms such as powerful outflows, the creation of HII regions, strong stellar winds, and supernova explosions (Zinnecker & Yorke, 2007). Consequently, they play a crucial role in enriching the interstellar medium with heavy elements, ultimately shaping the structure and evolution of their host galaxies (Kennicutt & Evans, 2012).

Despite their significance, many aspects of massive star formation remain poorly understood. These challenges arise because massive stars are rare, with only a few located within a few kiloparsecs of the Solar System. Moreover, they typically form in clusters, making it difficult to isolate their individual properties from those of their environments (Kurtz, 2000). Massive stars also evolve rapidly, reaching the main sequence while still deeply embedded in their natal molecular clouds (Motte et al., 2018). As a result, their earliest evolutionary stages occur behind hundreds of magnitudes of

visual extinction and can only be studied at far-infrared and submillimetre wavelengths (Lumsden et al., 2013).

One of the defining characteristics of massive stars is their ability to ionise their surroundings, creating bubbles of ionised hydrogen known as HII regions. These regions mark a key stage in stellar evolution, as they indicate that a massive star has reached the main sequence and is producing large quantities of Lyman continuum photons. The smallest and most compact of these regions are known as hypercompact HII (HC HII) regions (Kurtz, 2005a), which are the main focus of this thesis.

HC HII regions provide the earliest indication that a massive star has begun to ionise its surroundings, representing a critical stage in its development (Gaume et al., 1995). They appear as small, dense bubbles of ionised gas that expand outward, potentially impeding further accretion and helping to set the final mass of the star. However, their rarity and short lifetimes make them challenging to detect and study. Despite their significance, only a limited number of well-characterised HC HII regions exist, their small angular sizes result in low flux densities at low frequencies, and most large-scale radio surveys (e.g., THOR; Beuther et al. 2016, CORNISH; Purcell et al. 2013; Irabor et al. 2023, GLOSTAR; Medina et al. 2019) operate below 10 GHz, where HC HII regions remain optically thick and thus difficult to detect (Kurtz & Hofner, 2005).

This thesis aims to identify and characterise new HC HII regions using high-frequency radio observations. The targets are selected based on their association with methanol masers that are well-known tracers of deeply embedded massive stars (Breen et al., 2013).

1.1 THE INTERSTELLAR MEDIUM

The interstellar medium (ISM) is the vast expanse of gas, dust, and radiation that fills the space between stars in a galaxy. Rather than existing as a uniform medium, it is structured into distinct phases, each characterised by differences in temperature,

TABLE 1.1: Phases of the interstellar medium, including characteristic temperatures, particle densities, and masses. The masses correspond to the total mass of each ISM phase integrated across the Milky Way. Adapted from Klessen & Glover (2016) and references therein.

Phase	Temperature (K)	Particle Density (cm^{-3})	Mass ($M_{\odot}$)
Hot Ionised Medium	$\sim 10^6$	$\sim 10^{-2}$	3×10^6
Warm Ionised Medium	$\sim 8,000$	$0.2 - 0.5$	5×10^7
Warm Neutral Medium	$\sim 6,000$	$0.2 - 0.5$	2×10^8
Cold Neutral Medium	$50 - 100$	$20 - 50$	3×10^9
Molecular Clouds	$10 - 20$	$> 10^2$	3×10^9

density, and ionization. These phases, summarised in Table 1.1, provide a structured framework for classification; the table includes characteristic masses for each phase, which correspond to the total mass integrated across the entire Milky Way. The medium itself is highly turbulent, with gradual transitions rather than sharply defined boundaries. Its structure is shaped by processes such as turbulence, shocks, and magnetic fields, which drive the constant mixing and evolution of material across different phases (McKee & Ostriker, 2007).

While dust constitutes only a small fraction of the ISM, it plays a crucial role in its processes. Dust grains are composed primarily of silicates, graphite, and ice, with smaller contributions from metals and organic materials (Ferrière, 2001). These grains provide surfaces for key chemical reactions, including the formation of molecular hydrogen (H_2), which is essential for star formation (Herbst et al., 2005). In addition to supporting chemical reactions, dust plays a significant role in regulating the thermal balance of the ISM. It absorbs ultraviolet and optical radiation from stars and re-emits it as infrared radiation, which aids in the cooling of the ISM. This cooling effect is particularly important in dense regions, where it helps facilitate the collapse of molecular clouds and the formation of new stars. Furthermore, dust grains shield molecular hydrogen from the destructive effects of ultraviolet radiation, which would otherwise break apart the molecules and disrupt the chemical complexity of the ISM (Van Loo et al., 2013).

The heating of the ISM occurs through photoelectric heating, cosmic ray interactions, and shock-induced heating. Photoelectric heating, driven by far-ultraviolet photons, dominates in diffuse regions by ejecting electrons from dust grains (Wolfire

et al., 2010). Cosmic ray heating is more significant in shielded environments, ionising atoms and molecules (Padovani et al., 2020). Shock heating, from supernova remnants, stellar winds, and cloud collisions, injects turbulence and thermal energy into the gas (Draine, 2011). Cooling processes, especially infrared emission from dust, balance these heating mechanisms, radiating energy away from dense regions and maintaining thermal equilibrium throughout the ISM. The ISM is not uniformly distributed, with most molecular gas residing in giant molecular clouds (GMCs), the primary sites of star formation (Heyer & Dame, 2015). Within these clouds, filaments fragment into dense clumps, where high-mass stars form (André et al., 2014; Motte et al., 2018).

TABLE 1.2: The physical properties of clouds, clumps, and cores taken from Bergin & Tafalla (2007) and references therein.

Property	Clouds	Clumps	Cores
Mass ($M_{\odot}$)	$10^3 - 10^4$	50 – 500	0.5 – 5
Size (pc)	2 – 15	0.3 – 3	0.03 – 0.2
Mean Density (cm^{-3})	50 – 500	$10^3 - 10^4$	$10^4 - 10^5$
Gas Temperature (K)	≈ 10	10 – 20	8 – 12
Examples	Taurus, Oph, Musca	B213, L1709	L1544, L1498, B68

1.1.1 GIANT MOLECULAR CLOUDS (GMCs)

GMCs are the largest structures among the molecular clouds of the ISM and are the primary sites of star formation in galaxies. These vast reservoirs of gas and dust play a crucial role in the star formation process and dominate the molecular phase of the ISM. GMCs exhibit diverse shapes and sizes, typically spanning several to tens of parsecs, with relatively constant temperatures of approximately 15 K (Solomon et al., 1979). At these low temperatures, H_2 does not emit radiation because its energy levels are not excited enough to release photons. Consequently, H_2 cannot be used to directly probe the structure or mass of these clouds. Instead, astronomers rely on other molecules, such as carbon monoxide (CO), as tracers. Unlike H_2 , CO possesses a permanent dipole moment and exhibits rich rotational spectra, which can be excited even at low temperatures. These properties make CO an invaluable tool for studying the internal structure of GMCs (e.g., Lada, 1976; Roman-Duval et al., 2010). Estimates of GMC masses based on CO observations suggest a range of $10^3 - 10^4 M_{\odot}$. Furthermore, CO emis-

sion maps reveal that GMCs are not uniform but contain intricate internal structures composed of elongated filaments (Roman-Duval et al., 2010). Within these filaments, molecular clumps form as smaller, denser regions. The properties of these clumps are summarised in Table 1.2. Inside the molecular clumps are localized high-density regions known as molecular cores. These cores exhibit densities of $10^4\text{--}10^5\text{ cm}^{-3}$, masses of $0.5\text{--}5\text{ M}_\odot$, and sizes ranging from 0.03 to 0.2 pc (Bergin & Tafalla, 2007). The gravitational collapse of these cores leads to the formation of stars, as originally described by Shu (1977).

1.1.2 SUPPORT MECHANISMS WITHIN MOLECULAR CLOUDS

The variations in density within a molecular cloud give rise to regions with strong gravitational fields, which in turn lead to the formation of molecular cores. As a clump continues to accrete material from the surrounding molecular cloud, the mass and self-gravity of the core increase. Under the influence of gravity alone, a molecular cloud is expected to collapse on a free-fall timescale, t_{ff} , which can be expressed as:

$$t_{\text{ff}} = \sqrt{\frac{3\pi}{32G\bar{\rho}}}, \quad (1.1)$$

where $\bar{\rho} = \frac{3M}{4\pi R^3}$ is the initial density of a cloud, M is the mass, R is the radius, and G is the gravitational constant ($6.67 \times 10^{-11}\text{ N m}^2\text{ kg}^{-2}$). The estimated free-fall timescale for such clouds is approximately 1×10^6 years. However, this does not account for thermodynamic changes or internal support mechanisms within the cloud. Observations suggest that molecular clouds survive for up to 30 times longer than the free-fall timescale, implying the presence of support mechanisms that hinder the collapse of the cloud (Blitz & Shu, 1980). If the collapse of molecular clouds were unhindered, the Galactic star formation rate (SFR) would be highly efficient and much larger than the observed value of approximately $3\text{ M}_\odot\text{ yr}^{-1}$ (McKee & Ostriker, 2007). There are three main support mechanisms that enable molecular clouds to survive for periods much longer than their free-fall times, these are discussed below:

Thermal pressure

The first support mechanism is thermal pressure, which arises from the kinetic temperature of the gas. The thermal pressure, P , is given by:

$$P = nkT, \quad (1.2)$$

where n is the number density of particles, k is the Boltzmann constant ($1.38 \times 10^{-23} \text{ J K}^{-1}$), and T is the temperature of the gas. Essentially, the higher the gas temperature, the greater the pressure. However, molecular clouds typically maintain temperatures around $\sim 15 \text{ K}$. At such low temperatures, the thermal pressure is insufficient to counteract gravitational collapse (McKee & Ostriker, 2007).

Magnetic Fields

Magnetic fields are present throughout the Galaxy and can influence the stability of molecular clouds by either supporting or facilitating their collapse. Their ability to counteract gravity depends on the orientation of the magnetic field lines, as they only provide support against collapse in the direction perpendicular to these lines (Li et al., 2014). Although magnetic fields primarily affect charged particles, i.e., ions and free electrons, the majority of the gas in molecular clouds is neutral. The interaction between charged and neutral particles transfers the field's effect to the neutral gas, resisting the collapse in the perpendicular direction.

Turbulence

Turbulence affects both the large and small scales of the ISM. On large scales, turbulence provides support against global gravitational collapse, helping to stabilise giant molecular clouds and regulate star formation rates. At these scales, it is primarily driven by supernova explosions, which inject substantial energy into the ISM (Mac Low & Klessen, 2004; Elmegreen & Scalo, 2004). At intermediate scales, turbulence gives rise to hierarchical substructures, such as dense filaments and cores, which serve as the primary sites of star formation. In this regime, stellar winds and expanding HII regions are thought to be significant sources of turbulent energy (Padoan et al., 2014; Falceta-Gonçalves et al., 2014). On the smallest scales, turbulence dissipates, facili-

tating the outward transport of angular momentum and enabling material to accrete onto the forming protostar. Here, protostellar outflows are believed to play a key role in sustaining localised turbulence (Krumholz et al., 2005; Elmegreen & Scalo, 2004).

1.2 STAR FORMATION

Now that an understanding of the ISM has been established, we can begin to explore the processes that govern star formation. Star formation is a fundamental astrophysical process that takes place within molecular cores, which are the densest regions of the ISM (Bergin & Tafalla, 2007; Tan et al., 2014). This section provides an overview of the mechanisms driving the formation of low- and high-mass stars, their respective challenges, and the evolutionary sequences. Additionally, observational signposts across different stages of star formation will be highlighted, with a focus on the formation and expansion of HII regions.

1.2.1 GRAVITATIONAL COLLAPSE OF MOLECULAR CLOUDS

Due to density inhomogeneities within molecular clouds, certain regions exhibit a stronger gravitational field than others. These denser regions, known as molecular clumps, attract more gas and dust. As these clumps continue to accrete material from their surroundings, their mass and gravitational potential increase. Eventually, the gravitational pull becomes strong enough to overcome internal pressure. In the absence of support mechanisms against gravitational collapse, each clump would be expected to collapse rapidly into a single star. However, observations show that clumps do not always collapse immediately into a single star. Instead, they can survive for extended periods, and accumulate masses up to values of $10 - 1000 M_{\odot}$ before collapsing (Bergin & Tafalla, 2007).

For a molecular cloud to collapse under its own gravity, the balance between internal kinetic energy and gravitational potential energy must satisfy specific conditions.

This is mathematically represented below and is known as the virial theorem:

$$2K + U < 0, \quad (1.3)$$

where K is the kinetic energy, given by:

$$K = \frac{3}{2}NkT, \quad (1.4)$$

and U is the gravitational potential energy:

$$U = -\frac{3}{5}\frac{GM^2}{R}, \quad (1.5)$$

where N is the number of particles, k , T , G , M and R are as previously defined. For a cloud in virial equilibrium, the condition becomes:

$$3NkT = \frac{3}{5}\frac{GM^2}{R}. \quad (1.6)$$

If the kinetic energy is less than the gravitational energy, the cloud becomes unstable and begins to collapse. Conversely, if the kinetic energy exceeds the gravitational potential energy, the cloud resists gravitational collapse. To better understand the conditions for gravitational collapse, it is useful to introduce the Jeans mass (M_J). The Jeans criterion states that if the mass of the cloud exceeds the Jeans mass, gravitational forces will overcome the internal pressure, and the cloud will collapse. Therefore, the Jeans mass represents the minimum mass required for a cloud to initiate collapse. The Jeans mass is given by:

$$M_J = \left(\frac{5kT}{Gm}\right)^{3/2} \left(\frac{3}{4\pi\rho_0}\right)^{1/2}, \quad (1.7)$$

where m is the mean particle mass, and ρ_0 is the mean gas density. Once the cloud begins to collapse, it does not do so uniformly. Instead, smaller regions within the cloud, where local densities are higher, fragment into individual cores. These cores are the densest substructures within the collapsing clump and serve as the precursors to star

formation. At this stage, the Jeans mass remains critical in determining whether each core continues to collapse. As the collapse progresses, the cores evolve into protostars, accreting material from their surroundings and eventually forming individual stars.

1.2.2 LOW-MASS STAR FORMATION

In the previous section, we discussed how molecular clouds fragment into clumps and dense cores. The subsequent evolution of these cores into stars has been studied extensively, both theoretically and observationally. Historically, one of the most influential theoretical descriptions of low-mass star formation was the inside-out collapse model proposed by Shu (1977). Although this model is no longer regarded as a complete or realistic description of star formation in molecular clouds, it provides a useful conceptual framework for illustrating the key physical stages involved. Figure 1.1, adapted from Shu et al. (1987), summarises this idealised evolutionary sequence.

In the classical picture, star formation begins within a dense, approximately spherical core on spatial scales of order ~ 1 pc, with a mass exceeding the local Jeans mass, $M_{\text{core}} > M_J$ (panel a of Fig. 1.1). The Shu model assumes that such cores are quasi-static and supported primarily by thermal pressure prior to collapse. Once gravitational forces dominate, collapse proceeds from the centre outward in a self-similar manner, with inner regions collapsing first due to shorter free-fall times (panel b of Fig. 1.1). In this scenario, material accretes smoothly through a rotating envelope, forming a centrally concentrated object.

However, extensive observational and numerical work over the past two decades has demonstrated that these assumptions are strongly idealised. Dense cores are now known to be embedded within a supersonically turbulent interstellar medium, are often filamentary rather than spherical, and experience highly time-variable, asymmetric accretion. Turbulence, magnetic fields, and large-scale gas flows provide significant non-thermal support and dynamically assemble cores, rather than allowing them to evolve in isolation from near-equilibrium initial conditions. As a result, the inside-out collapse model is no longer considered the physically favoured mechanism for low-mass star formation, but rather a simplified reference model that captures the basic sequence

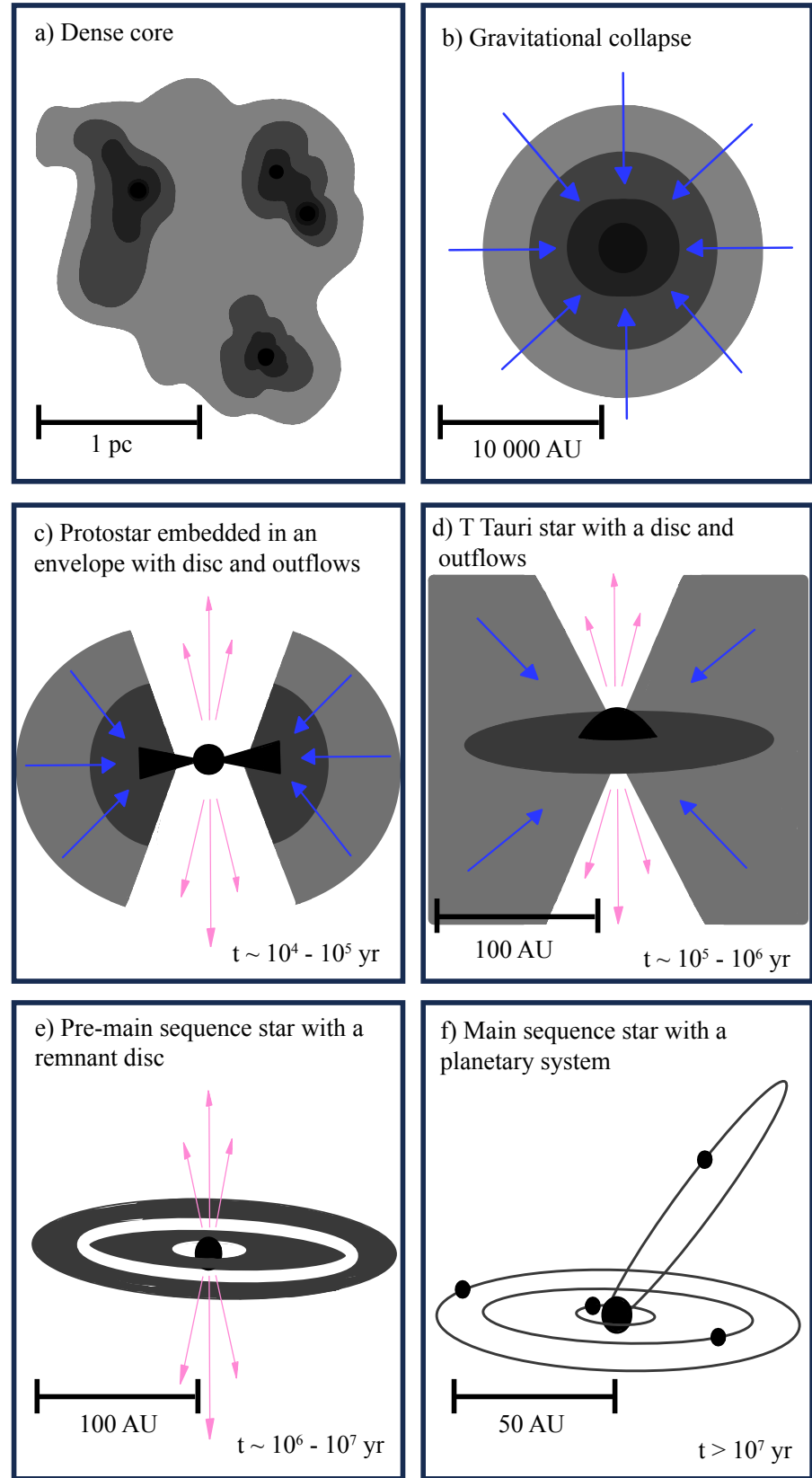


FIGURE 1.1: Schematic of the evolutionary sequence of low-mass star formation. Early stages involve dense cores undergoing gravitational collapse, leading to the formation of a protostar embedded in an envelope with a disc and outflows. The system evolves into a T Tauri star with a disc and continued outflows, followed by a pre-main sequence star with a remnant disc. The final stage is a main sequence star with a planetary system. The greyscale indicates the density distribution, with darker regions corresponding to denser material, while the scale bars and approximate timescales indicate the characteristic size and duration of each stage. This schematic is recreated from Shu et al. (1987).

of collapse and protostellar evolution.

Despite these limitations, the physical processes illustrated by the Shu framework remain broadly relevant. As collapse proceeds, increasing densities cause the gas to become optically thick, and the initially isothermal collapse transitions to an adiabatic phase, suppressing further fragmentation on small scales. This leads to the formation of a transient hydrostatic core at the centre, where thermal pressure balances gravity. Continued accretion from the surrounding envelope generates an accretion shock at the core surface, converting kinetic energy into heat and dominating the luminosity at this stage. When the central temperature reaches ~ 2000 K, molecular hydrogen dissociates, reducing pressure support and triggering a second collapse. The system subsequently re-establishes hydrostatic equilibrium, forming a compact protostar (panel c of Fig. 1.1).

As the protostar evolves, accretion from its surroundings continues, and conservation of angular momentum leads to the formation of a circumstellar disc. This disc regulates the transfer of material onto the central object and provides the conditions necessary for launching bipolar outflows along the rotation axis (panel d of Fig. 1.1). These outflows, driven by accretion and magnetic processes, play a crucial role in removing angular momentum and dispersing the surrounding envelope, thereby influencing the final stellar mass.

When the core temperature rises to approximately 10^6 K, deuterium fusion begins, marking the transition to the pre-main sequence phase. By this stage, most of the envelope has been accreted or expelled, and the object is observationally classified as a T Tauri star (panel e of Fig. 1.1). Continued disc evolution, stellar winds, and radiative feedback gradually disperse the remaining circumstellar material, allowing the star to contract onto the main sequence, where it will spend the majority of its lifetime (panel f of Fig. 1.1).

While theoretical models of collapse continue to evolve, observational studies have provided a robust and largely model-independent framework for describing low-mass star formation. Infrared and submillimetre observations have revealed a clear evolutionary sequence based on the spectral energy distributions (SEDs) of young stellar

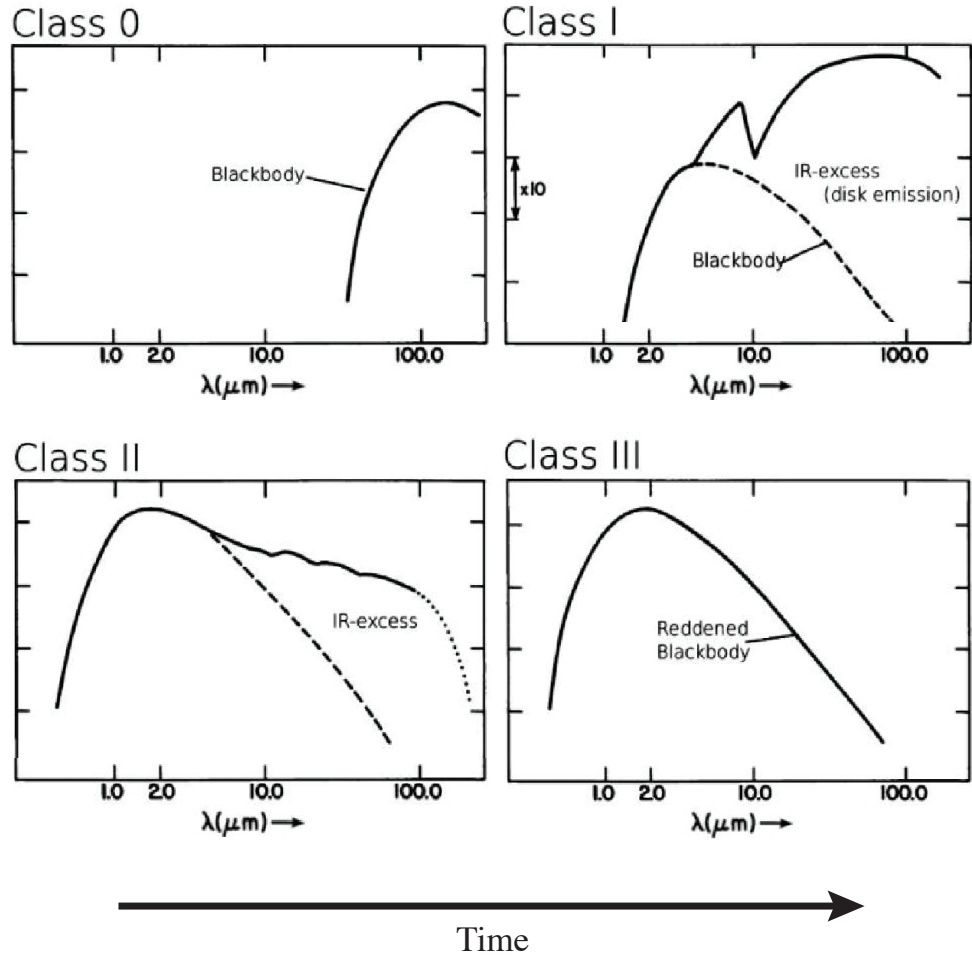


FIGURE 1.2: Examples of spectral energy distributions from the four evolutionary stages of low-mass star formation, corresponding to panels b–e of Fig. 1.1. These SEDs have been adapted from Lada (1987) and Shu et al. (1987).

objects. Lada (1987) introduced a classification scheme based on the infrared spectral index between 1–20 μm , defining the Class I, II, and III stages. This was later extended by Andre et al. (1993), who identified an earlier, deeply embedded Class 0 phase using submillimetre observations. Together, these studies established an observational classification scheme dividing the evolution of low-mass stars into four distinct classes, based on their SEDs, as illustrated in Fig. 1.2. This framework remains widely used, as it is grounded in observable properties rather than the assumptions of any particular theoretical collapse model.

1.2.3 HIGH-MASS STAR FORMATION

Massive stars ($> 8 M_{\odot}$, $> 10^3 L_{\odot}$) play a crucial role in shaping the structure and evolution of their host galaxies (Kennicutt & Evans, 2012). Through their powerful outflows, stellar winds, and chemical enrichment of the interstellar medium (ISM), they regulate star formation within clusters and drive feedback processes that influence their surrounding environments (McKee & Ostriker, 2007). Massive stars are responsible for producing the heaviest elements, which are returned to the ISM through stellar winds and supernova explosions. However, the formation of massive stars is still not well understood. Unlike low-mass stars, massive stars are relatively rare, evolve rapidly, and reach the main sequence while still deeply embedded in their natal environments, making them difficult to observe. High-mass stars also form almost exclusively in clusters, making it challenging to separate the properties of individual stars from their host clusters. The earliest stages of their formation can only be studied at far-infrared and (sub)millimetre wavelengths, where the deeply embedded phases can be probed (Motte et al., 2018). Overcoming the observational challenges of massive star formation requires large-scale, multi-wavelength surveys of the Galactic plane to detect embedded high-mass stars and high-resolution observations to examine their properties. Some of these surveys will be discussed in more detail in Section 1.4.

Massive stars are both intrinsically rare and physically difficult to form. The rarity of massive stars is quantified by the initial mass function (IMF), which describes the distribution of stellar masses at birth and is commonly expressed as dN/dM , where dN is the number of stars formed within the mass interval M to $M + dM$. Observationally, the IMF rises towards lower stellar masses and declines steeply at higher masses, indicating that massive stars form far less frequently than low-mass stars (Salpeter, 1955; Kroupa, 2001). However, while the IMF describes the relative numbers of stars formed at different masses, it does not explain the physical processes required to assemble enough material into a single high-mass object.

Massive stars require substantially larger reservoirs of material than their low-mass counterparts. For example, forming a $30 M_{\odot}$ star would require a dense core with a mass of approximately $180 M_{\odot}$, assuming a star formation efficiency (SFE) of

17% (Wells et al., 2022). Forming and maintaining such massive cores is challenging within molecular clouds, where turbulence and fragmentation during gravitational collapse tend to disperse material into multiple smaller cores rather than allowing it to accumulate into a single stable object. Even when sufficiently massive cores do form, an additional challenge arises from the intense radiative and mechanical feedback generated by the growing protostar itself.

The formation of high-mass stars is also influenced by the timescales that govern their evolution. For high-mass protostars, the Kelvin-Helmholtz (KH) timescale, which represents the time required for a protostar to reach thermal equilibrium, is much shorter than the free-fall timescale. The KH timescale can be expressed as:

$$t_{\text{KH}} = \frac{GM^2}{RL}, \quad (1.8)$$

where L is the luminosity (W) and all the other variables are as previously defined. As a result, high-mass stars continue to accrete mass from the free-falling envelope after reaching the main sequence. Once a high-mass protostar reaches the main sequence, the luminosity it produces generates sufficient radiation pressure to significantly slow or even halt the infall of material from the surrounding envelope (Wolfire & Cassinelli, 1987).

Theoretical models predict that radiation pressure should set an upper limit of around $7 M_{\odot}$ on the mass a star can gain through the direct infall of material, assuming accretion occurs without the influence of a circumstellar disc (Wolfire & Cassinelli, 1987). However, observations of stars with masses exceeding this limit by more than an order of magnitude challenge this prediction. Such observations demonstrate that radiation pressure does not entirely prevent stellar growth. While accretion and infall adequately explain the formation of low- and intermediate-mass stars, they fail to account for the formation of stars significantly larger than $7 M_{\odot}$. Two primary theories are widely discussed in the literature that address this issue and are briefly described below.

Monolithic collapse (McKee & Tan, 2003) suggests that a specific region within a molecular cloud becomes gravitationally bound, causing the formation of a dense

core. In this model, the material available for accretion is limited to this collapsing core, with only the closest stars in the cluster competing for the infalling material. The theory suggests that the mass required to form a massive star is largely determined by the conditions of the core at the beginning of star formation, meaning the final mass of the star is closely linked to the initial conditions of the collapsing core. Competitive accretion (Bonnell et al., 1997, 2001) argues that the position of a star within its natal cloud dictates how much material it can gather. Protostars near the centre of the cloud benefit from stronger gravitational potentials, allowing them to draw in larger amounts of material from the surrounding gas. In contrast, protostars located toward the edges of the cloud are limited in the mass they can accrete due to their weaker gravitational influence. Since the gas reservoir within the cloud is finite, protostars naturally compete for the available material. Central stars gain an advantage because of their location, allowing them to accumulate more mass. This process leads to what is often described as a “rich get richer” effect, where the largest and most massive stars are typically found near the cluster’s centre. Observations support this idea, as massive stars are often located in clusters rather than forming in isolation (Lada & Lada, 2003; Motte et al., 2018).

The exact process by which massive stars form remains uncertain, despite extensive research over the past decades. Several reviews have provided comprehensive summaries at different stages, for example; McKee & Tan (2003); Zinnecker & Yorke (2007); Motte et al. (2018); Pineda (2023); Beuther et al. (2025). While no single model fully explains all observations, it is likely that massive star formation involves a combination of the two scenarios described above. Initially, a star may accrete material from a localized reservoir within a collapsing core, aligning with the monolithic collapse model. Over time, as the star evolves and interacts with its environment, additional material from the surrounding molecular cloud may become available for accretion, consistent with models of competitive accretion.

Modern models of high-mass star formation have therefore moved beyond a simple scaled-up version of the low-mass, inside-out collapse picture. Current work emphasises that massive stars form through dynamic, multi-scale accretion from fil-

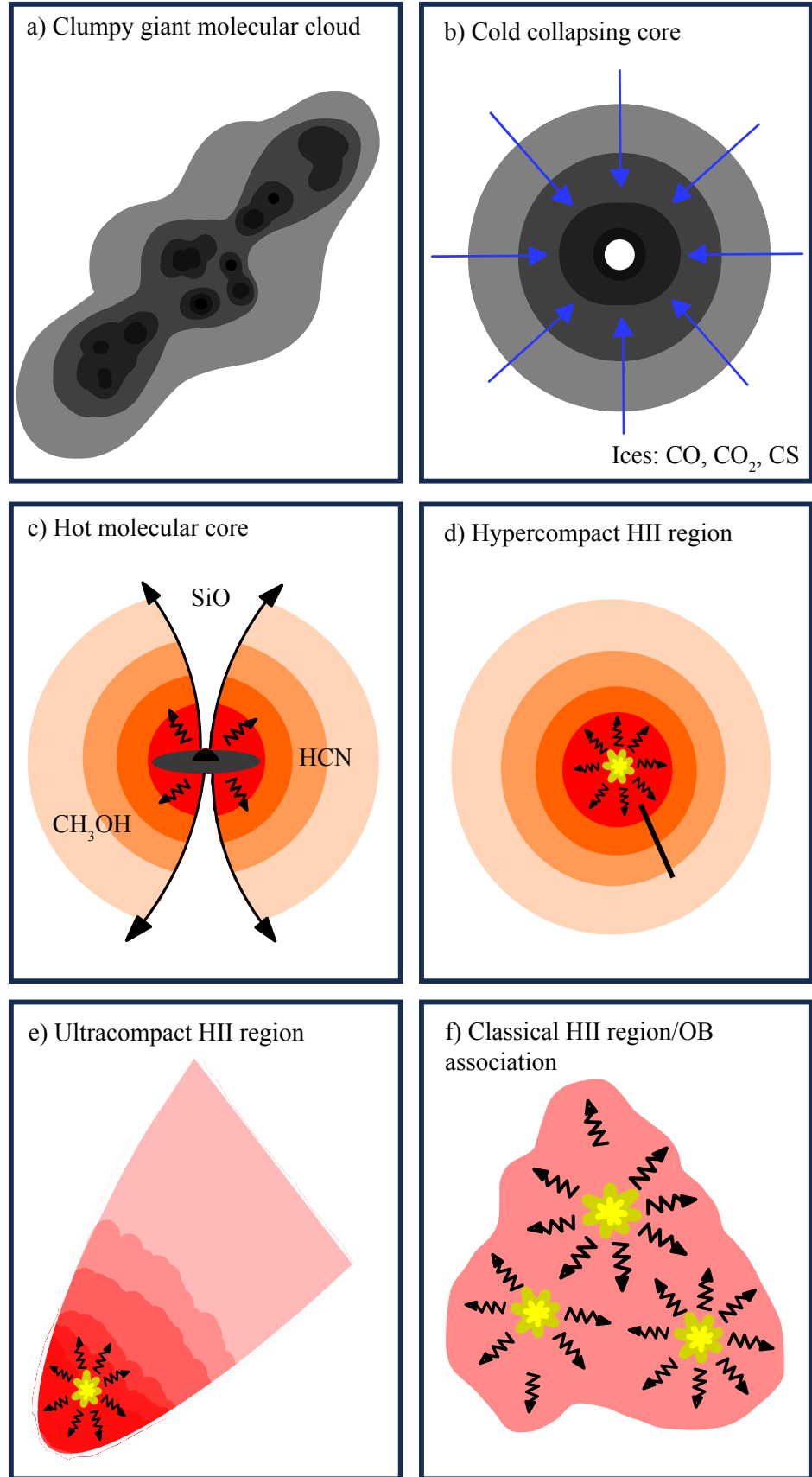


FIGURE 1.3: Schematic of the evolutionary sequence of high-mass star formation. The earliest stages correspond to clumpy molecular clouds and collapsing cores, progressing to more evolved stages, such as hot molecular cores and HII regions. The greyscale represents the distribution of cold gas and dust, with darker regions indicating higher densities. The ionised gas is shown in red at later stages, with orange indicating regions that are not fully ionised, as the gas closest to the star becomes ionised first. This schematic is recreated from Purcell et al. (2013).

amentary and clustered environments, with material often channelled through discs while feedback is already active. The main remaining barriers are both theoretical and observational. Theoretically, models must explain how accretion continues despite radiation pressure, ionisation, stellar winds, outflows, magnetic fields, and fragmentation. Observationally, the earliest stages are deeply embedded, distant, short-lived, and usually confused by clustered star formation, making it difficult to isolate individual protostars and measure their accretion rates, disc properties, multiplicity, and feedback. Distinguishing between ionised jets, stellar winds, and the youngest HCHII regions remains particularly important for establishing a reliable evolutionary sequence.

1.2.4 OBSERVATIONAL SIGNPOSTS OF HIGH-MASS STAR FORMATION

The processes involved in the formation of high-mass stars are not directly observable due to the dense envelopes of material surrounding high-mass protostars. Instead, our understanding of these processes is based on observing the effects they have on their surroundings. Figure 1.3 provides a schematic overview of the evolutionary stages of high-mass star formation, from the initial clumpy molecular cloud phase, through core collapse and the formation of hot molecular cores, to the formation and expansion of HII regions. Each stage corresponds to specific observational signposts, such as infrared emission, masers, hot cores, outflows and HII regions, which are discussed in detail in the following paragraphs:

Infrared emission

One of the earliest observable signposts of high-mass star formation is infrared emission, which arises from deeply embedded protostars forming within dense molecular clouds. These clouds are highly opaque to optical and ultraviolet radiation because their concentration of dust and gas efficiently scatters and absorbs shorter-wavelength light. However, dust grains within the clouds absorb this energy and re-emit it at longer infrared wavelengths, which can escape the cloud more easily.

The APEX Telescope Large Area Survey of the Galaxy (ATLASGAL) survey (Schuller et al., 2009; Urquhart et al., 2018, 2022) has classified dense clumps, where this

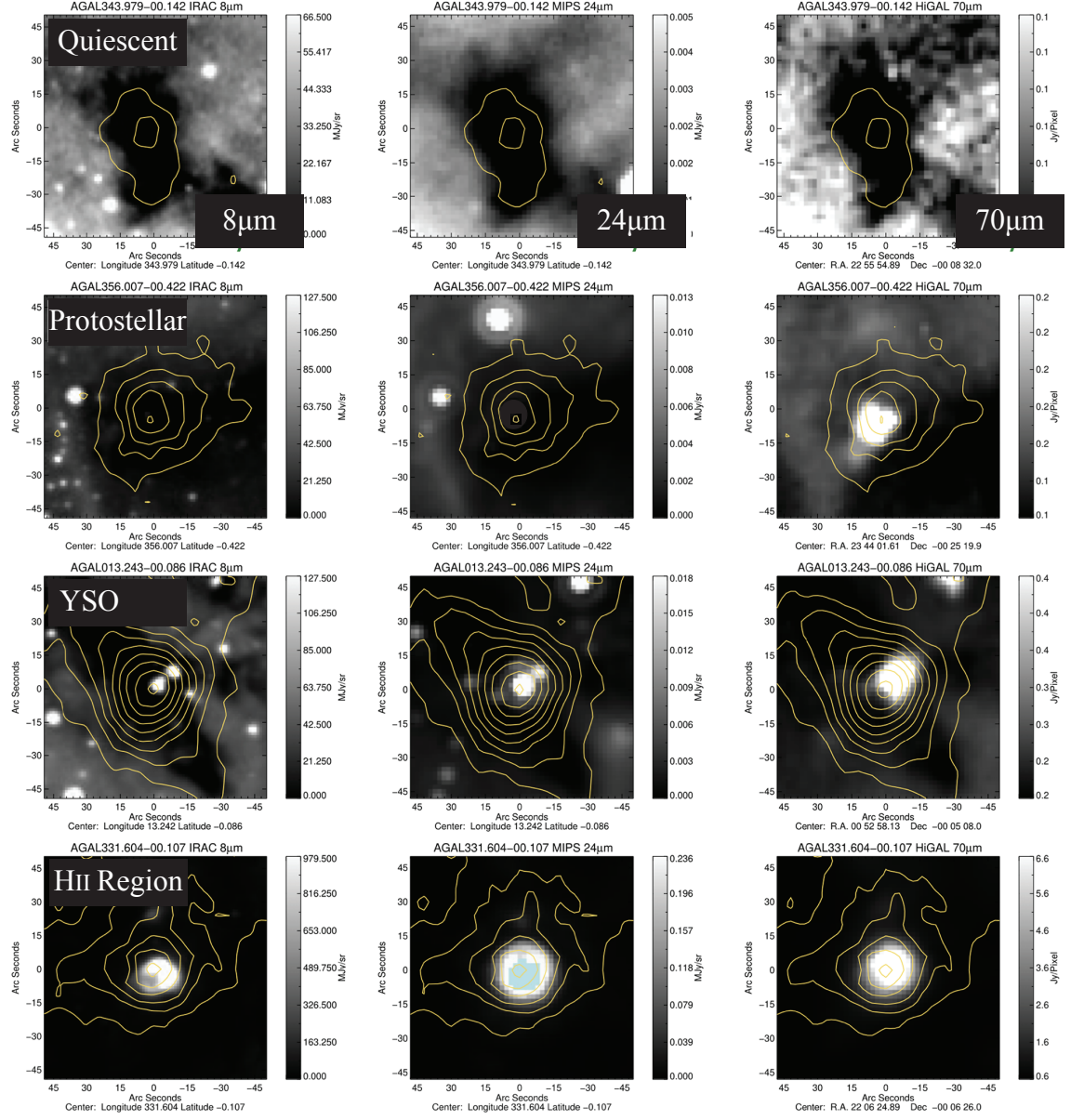


FIGURE 1.4: Mid-infrared images of ATLASGAL sources used to define the four observed evolutionary stages. Rows show quiescent, protostellar, YSO, and HII-region clumps from top to bottom, while columns show 8, 24, and 70 μm emission from left to right. The contours represent the distribution of 870 μm dust emission traced by ATLASGAL. Adapted from Urquhart et al. (2022).

infrared emission originates, into four evolutionary stages based on multi-wavelength data analysis. Using mid-infrared images ($3\text{--}70\ \mu\text{m}$) from the Galactic Legacy Infrared Midplane Survey Extraordinaire (GLIMPSE; Churchwell et al. 2009), MIPS-GAL (Carey et al., 2009), and Herschel infrared Galactic Plane (HiGAL; Molinari et al. 2010a, 2016) surveys, clumps are categorised as quiescent, protostellar, YSO, or HII regions. Quiescent clumps are cold ($10\text{--}15\ \text{K}$), lack embedded objects, and appear dark at $70\ \mu\text{m}$ (as seen in the top row of Fig. 1.4). Protostellar clumps mark the initial stages of star formation, where a protostar begins to heat its natal clump, making it detectable at $70\ \mu\text{m}$ but not yet at shorter wavelengths (second row of Fig. 1.4). YSO clumps are warmer, becoming visible at both $3\text{--}8$ and $24\ \mu\text{m}$, where their emission appears as unresolved point sources (third row of Fig. 1.4). Finally, HII regions, the most evolved sources in the embedded stages, are the warmest and are detectable across all mid-infrared wavelengths (bottom row of Fig. 1.4).

Maser emission

Molecular maser species such as H_2O , OH and CH_3OH (hereafter methanol) are compact and very bright objects that are known to signpost regions of high-mass star formation (Breen et al., 2013; Paulson & Pandian, 2020). Newly formed high-mass stars are able to provide the physical conditions necessary to maintain the population inversions required for masing. Masers are usually confined to very dense regions that have particle number densities between $10^6\text{--}10^9\ \text{cm}^{-3}$. Each maser species arises under distinct physical conditions, resulting in unique spectral characteristics that allow them to be differentiated from one another. Consequently, molecular masers can provide valuable insights into the environment, kinematics and feedback processes associated with massive star formation. H_2O masers are collisionally pumped and the conditions required to excite them are high densities ($\sim 10^7\ \text{cm}^{-3}$) and temperatures up to $500\ \text{K}$ (Elitzur et al., 1992). These conditions are exclusively found in the shocked gas associated with molecular outflows (Claussen, 2002). Methanol masers have been divided into two classes based on their pumping mechanisms: Class I methanol masers, which are collisionally pumped, are associated with outflows (Menten, 1991), and are found at the interfaces of shock fronts where outflowing material interacts with the

surrounding interstellar medium (Cragg et al., 1992). Class II methanol masers are pumped by infrared radiation and require high temperatures and densities to be stimulated (Sobolev & Deguchi, 1994). These conditions are likely to be found between 100–1000 au from the high-mass protostellar object and are signposts of ongoing disc accretion (Breen et al., 2013). The most well known Class II methanol masers occur at frequencies of 6.7 GHz and 12.2 GHz, while Class I methanol masers occur at 36 GHz, 44 GHz, and 95 GHz. OH masers are also collisionally pumped and are widely recognised to trace shocked gas in the interface between neutral hydrogen and molecular hydrogen known as photodissociation regions (PDRs; Frail & Mitchell 1998). OH masers are thought to trace a slightly more evolved evolutionary stage than the class II CH₃OH masers.

Hot cores

Hot molecular cores are defined as compact objects, with diameters ≤ 0.1 pc, particle densities $\geq 10^7$ cm⁻³, temperatures ≥ 100 K and masses between $5\text{--}10 \times 10^2 M_{\odot}$ (Kurtz, 2000). These regions, heated internally by a central massive protostar, are precursors to UC HII regions. As the protostellar object accretes material within the cloud, the infall motion and radiation heat the surrounding core, leading to high temperatures and rich molecular complexity. These temperatures cause complex molecular species to evaporate from the ice mantles on dust grains. During this phase, the protostar continues to accrete material, and the associated accretion disc system gives rise to the formation of discs, outflows, and shocks.

Outflows and Jets

Molecular outflows are one of the most prominent observational signposts of active star formation. As the protostar continues to accrete material, the build-up of angular momentum and the influence of magnetic fields lead to the formation of collimated outflows and jets (Beuther et al., 2007; Peters et al., 2011). These outflows are driven by the transfer of energy from the accretion disc, where material is funnelled along the poles due to the rotation of the protostar and the orientation of magnetic field lines. Observations of highly collimated molecular outflows provide indirect evidence for the presence of small-scale discs around massive protostars (Goddi, 2020). Addi-

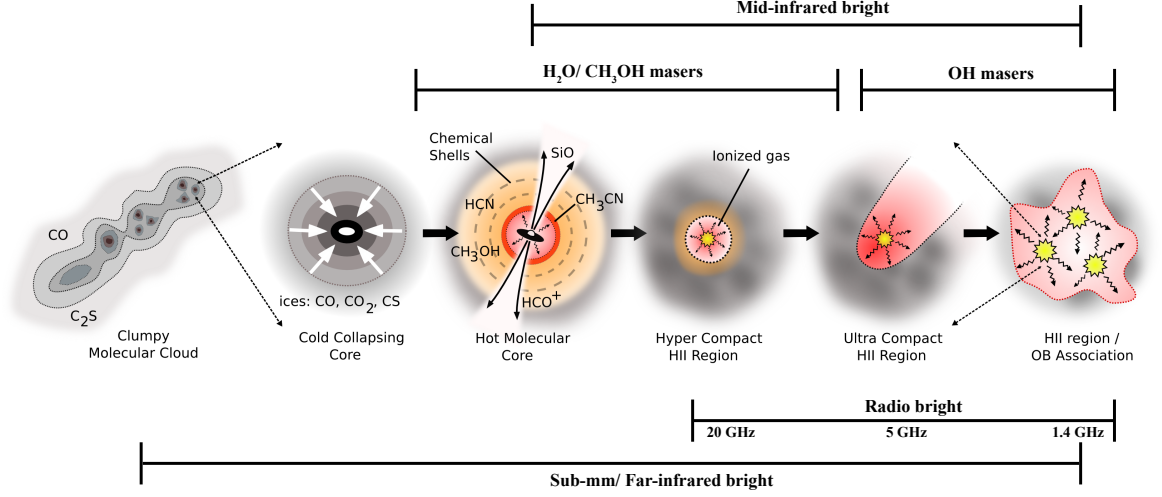


FIGURE 1.5: Schematic of the evolutionary sequence of massive star formation. The colours and symbols are as described in Fig. 1.3. Infrared and radio surveys are sensitive to the more evolved stages shown to the right while submillimetre surveys are sensitive to all evolutionary stages. This schematic was originally presented by Purcell et al. (2013) and has been adapted to show the tracers and signposts as seen in Urquhart (2024).

tionally, velocity gradients perpendicular to outflows, elongated compact emission, and outflow orientations perpendicular to maser distributions further support the existence of embedded accretion discs (Beltrán & de Wit, 2016; Yang et al., 2022).

Evidence of outflows can be detected using various tracers, revealing their structure, kinematics, and interactions with the surrounding medium. In the infrared, shocked gas in outflows is identified by excess emission at specific wavelengths. A well known example is the $4.5\,\mu\text{m}$ band, which shows strong emission from rotationally excited H_2 ($v = 0-0$) and CO ($v = 1-0$) transitions. The Extended Green Object (EGO) catalogue (Cyganowski et al., 2008) has identified over 300 sources using GLIMPSE survey data, characterised by excess $4.5\,\mu\text{m}$ emission, serving as tracers of shocked gas in protostellar outflows. While the $4.5\,\mu\text{m}$ band highlights shocked gas in outflows, CO bandhead emission at $2.3\,\mu\text{m}$ originates in warm ($T = 2500-5000\,\text{K}$), dense gas ($\sim 10^{11}\,\text{cm}^{-3}$; Chandler et al. 1993), providing crucial insight into the physical conditions within accretion discs and the immediate circumstellar environment.

In addition, molecular line observations provide further evidence of outflow activity. High-velocity emission in the wings of molecular lines, such as CO and SiO , is a widely used tracer of outflows across various stages of massive star formation (Snell et al., 1980; Zhang et al., 2001; Maud et al., 2015; Yang et al., 2018; Li et al., 2018).

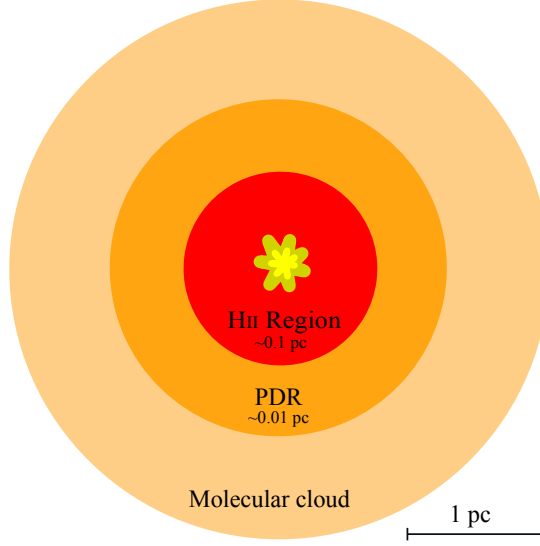


FIGURE 1.6: Structure of an HII region and its surrounding environment, showing the HII region (~ 0.1 pc), the photodissociation region (PDR, ~ 0.01 pc), and the molecular cloud (~ 1 pc).

These outflows are observed from the earliest infrared dark cloud phase (Beuther, 2011; Duarte-Cabral et al., 2013; Tan et al., 2016) to hot molecular cores (Kurtz, 2000) and the UC HII region stage (Codella et al., 2004; Yang et al., 2018). CO rotational transitions, such as $^{12}\text{CO}(2-1)$ and $^{12}\text{CO}(3-2)$, are commonly used to trace large-scale outflow structures, providing insights into both the shocked gas in the outflow lobes and the warm, dense gas near the protostar. SiO emission, particularly in the $J = 2-1$ transition, is often enhanced in shocked regions, making it a key tracer of high-velocity shocks in the inner outflow regions where the interaction with the surrounding material is most intense (Zhang et al., 2019b). Molecular masers, EGOs, and outflows are closely linked in the early stages of massive star formation, as each traces different aspects of accretion and feedback processes. Masers pinpoint regions of high density and excitation conditions, while EGOs highlight shocked gas in outflows. Figure 1.5 presents a schematic illustrating the relationship between masers, EGOs and molecular outflows in the context of massive star formation evolution.

1.3 HII REGIONS

The effective temperatures of massive O- and B-type stars enable them to emit UV photons with energies exceeding 13.6 eV, which are sufficient to ionise the surrounding gas within molecular clouds. The volume of ionised hydrogen surrounding these stars is known as an HII region. In an idealized model, this region takes the form of a Strömgren sphere. As the star begins to emit ionising radiation, it gradually photoionises the neutral hydrogen (HI) into ionised hydrogen (HII) until the ionised region reaches the Strömgren radius (R_s ; Strömgren 1939). The Strömgren radius is defined as the point where the rate of ionising photons emitted equals the rate of recombination. This process can be expressed by the equilibrium of ionization and recombination rates, given as:



where $h\nu$ represents a photon with energy greater than 13.6 eV, resulting in ionization ($\rightarrow$) and recombination ($\leftarrow$) between a proton and electron.

Between the ionised hydrogen and the surrounding molecular hydrogen exists a thin layer of neutral hydrogen, called PDRs. A simple schematic of this is shown in Fig. 1.6. In the simplest case, where the HII region consists entirely of hydrogen and all ionising photons originate from a single source, the ionization rate I and the recombination rate R are given by:

$$I = \frac{3N_{\text{Ly}}}{4\pi R_s^3} \quad \text{and} \quad R = n_e^2 \alpha_{\text{H}}, \quad (1.10)$$

where N_{Ly} is the Lyman continuum photon flux (s^{-1}), n_e is the electron density (cm^{-3}), and α_{H} is the recombination coefficient ($\text{cm}^3 \text{s}^{-1}$), which measures how efficiently free electrons recombine with protons to form neutral hydrogen and depends primarily on the gas temperature. By equating these two rates and rearranging for the

Strömgren radius R_s , we find:

$$R_s = \left(\frac{3N_{\text{Ly}}}{4\pi n_e^2 \alpha_H} \right)^{\frac{1}{3}}. \quad (1.11)$$

The size of the initial HII region is fundamentally determined by the number of Lyman continuum photons emitted by the central star and the density of the surrounding medium. A larger N_{Ly} flux leads to a larger HII region, as more Lyman continuum photons ionise the hydrogen in the surrounding gas. The number of Lyman photons is correlated with the star's spectral type, which is determined by the surface temperature. O- and B-type stars predominantly emit ultraviolet light due to their high surface temperatures, typically ranging from 15,000 K to 50,000 K (Panagia, 1973). Whereas cooler stars (e.g., K- and M-types) primarily radiate in the infrared. Stars of spectral type B3 or earlier, with luminosities exceeding $10^3 L_\odot$, are capable of sustaining an HII region, with earlier O-type stars producing significantly more ionising photons and forming larger HII regions (Sternberg et al., 2003).

In reality, the structure of an HII region is affected by additional factors, such as helium fraction, dust, and other metals. Although helium is less abundant than hydrogen ($n_{\text{He}} \sim 0.1n_{\text{H}}$), its higher ionization cross-section makes it easier to ionise (Deharveng et al., 2000). For stars producing photons with energies above 24.6 eV, helium can also become ionised and may contribute significantly to the ionisation structure. For HII regions around stars later than O6, the regions consist of ionised hydrogen with a layer of neutral helium. In contrast, for earlier O-type stars, both hydrogen and helium are fully ionised. Dust grains also influence the structure of HII regions. UV photons that would typically ionise the surrounding gas are often absorbed by dust and re-emitted as submillimetre infrared radiation, which lacks the energy to ionise hydrogen. This absorption reduces the effective size of the HII region. However, the re-emitted infrared photons provide a means to observe embedded HII regions. Metals such as carbon, nitrogen, and oxygen, while not abundant enough to significantly impact the ionization structure, contribute to optical line emissions. However, for distant nebulae, much of this optical emission is diminished due to interstellar dust extinction.

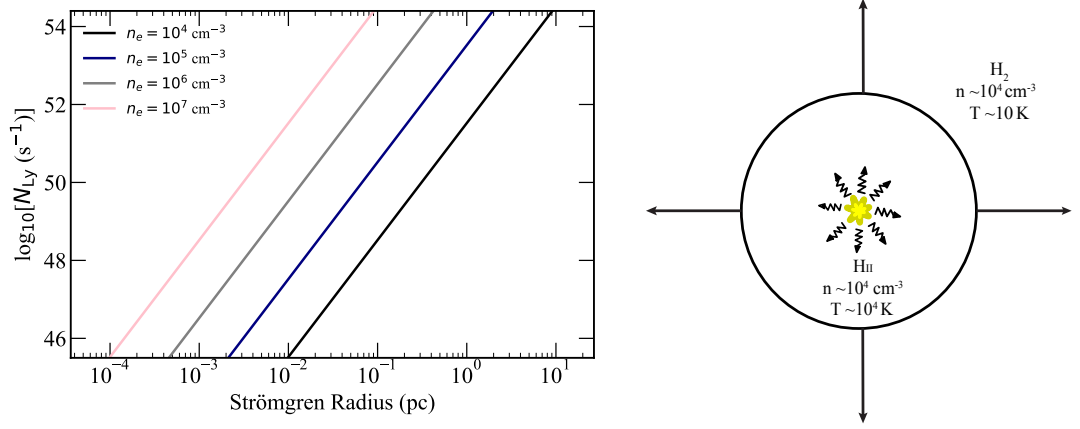


FIGURE 1.7: Left: Distribution of Strömgren radii as a function of Lyman continuum photon flux. The plot illustrates how varying electron densities influence the initial Strömgren radius, depending on the initial Lyman continuum photon flux. Right: A simple schematic of an expanding HII region.

1.3.1 EXPANSION OF HII REGIONS

Once the central star turns on, the number of Lyman continuum photons remains constant, defining the initial Strömgren radius. The left panel of Fig. 1.7 shows the relationship between the Strömgren radius and the Lyman continuum photon flux across different electron densities for a spherical HII region. These radii represent the minimum size of the ionised region that a massive star can sustain, given the electron density of the surrounding medium. However, real HII regions can expand well beyond this theoretical limit, sometimes reaching tens of parsecs. So, what factors, beyond ionising photons alone, could drive this expansion?

The primary mechanism behind this expansion is thermal pressure, as previously described in Eq. 1.2. Inside the HII region, ionising radiation heats the gas to temperatures around 10^4 K, while the surrounding molecular gas remains at approximately 10 K (Goldsmith, 1987). The pressure inside the HII region is therefore $\sim 1,000$ times greater than the external pressure, driving the expansion of the region into the surrounding neutral material. As a result, the region grows beyond its initial Strömgren radius over time. A simple schematic of this expansion is presented in the right panel of Fig. 1.7.

The left panel of Fig. 1.8 illustrates the relationship between the expansion diameter and the Lyman continuum photon emission rate over various timescales, ranging

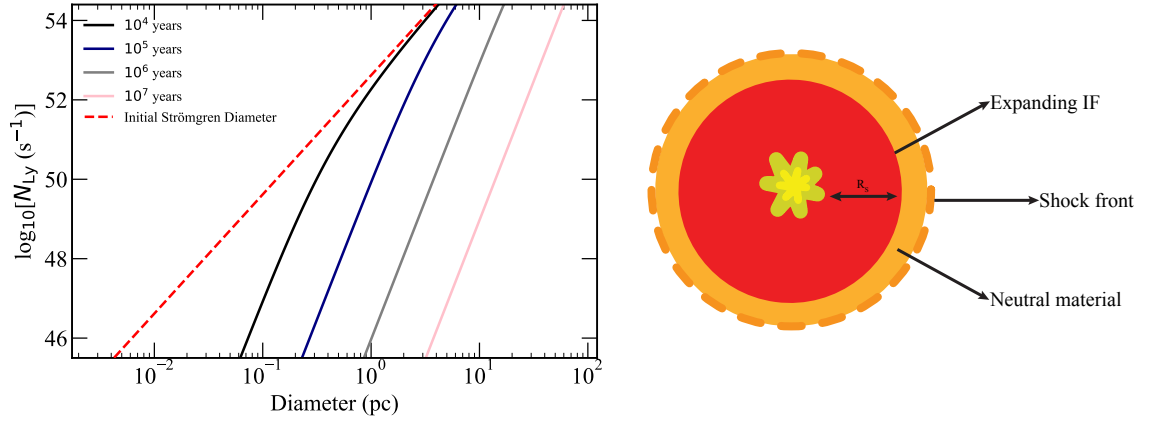


FIGURE 1.8: Left: Expansion of an HII region over time, showing the transition from R-type to D-type phases. The red dashed line represents the initial Strömgren diameter, marking the equilibrium boundary where the ionization front first forms. Right: Schematic representation of the ionization front and shock propagation.

from 10^4 to 10^7 years. The expansion is modelled using the Dyson & Williams (1997) equation for pressure-driven expansion, assuming a fixed electron density of 10^5 cm^{-3} , a recombination coefficient of $\alpha = 2.7 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$, and a sound speed in ionised gas of 10 km s^{-1} . This formalism describes how the ionization front initially expands rapidly before slowing due to the accumulation of neutral gas at the boundary. The expansion radius as a function of time follows:

$$R(t) = R_s \left(1 + \frac{7C_i t}{4R_s} \right)^{4/7}, \quad (1.12)$$

where $R(t)$ is the radius of the expanding HII region at time t and C_i is the sound speed in the ionised gas. Initially, the region expands rapidly, as seen from the steep slopes at early times, characteristic of the R-type phase. However, as time progresses, the expansion slows, and the curves flatten, indicating the transition to the D-type phase. The pressure gradient between the ionised and neutral gas drives this expansion, causing the ionization front to move outward while decelerating over time.

However, in reality, HII regions are often embedded in clumpy molecular clouds with varying densities, which significantly affect their expansion. The inhomogeneous nature of the surrounding medium means that the region may not expand symmetrically. Deharveng et al. (2010) highlight how simple models fail to capture the irregular shapes observed in real HII regions, such as the “fingers” and “elephant trunks” seen

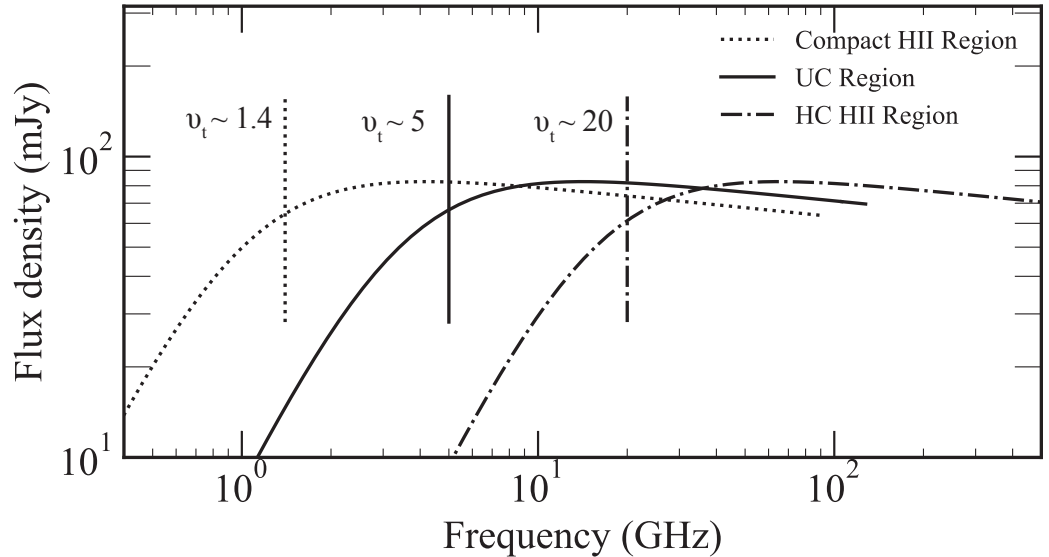


FIGURE 1.9: Radio spectrum of thermal bremsstrahlung emission from a spherical and homogeneous HII region. The dotted, solid and dot-dashed lines correspond to a compact, UC and HC HII region, respectively. The turnover frequencies are indicated by the vertical lines on each curve.

in regions like M16, which arise due to instabilities at the ionization front caused by interactions with dense clumps of gas. These irregularities are further influenced by magnetic fields, which suppress gas accumulation perpendicular to the magnetic field lines, leading to elongated, non-spherical expansions (Krumholz et al., 2007). While theoretical models are useful for understanding the formation and evolution of HII regions, their observational classification provides key insights into their physical properties. By studying their radio continuum emission, astronomers can track their evolution and distinguish between different types. In the following section, we outline the main observational stages of HII regions and how they are characterised.

1.3.2 OBSERVATIONALLY DEFINED STAGES

HII regions are powerful emitters of radio free-free emission, allowing them to be detected even when deeply embedded within their surrounding molecular clouds. Their characterisation requires observations across multiple wavelengths. In particular, they exhibit strong mid-infrared emission due to the absorption of stellar radiation by dust grains and its subsequent re-emission.

One key feature of HII regions is their radio SEDs. The intensity of emission, I_ν ,

which represents the flux density per unit frequency, follows $I_\nu \propto \nu^2$ at low frequencies in the optically thick regime, meaning the intensity increases rapidly with frequency. At higher frequencies, the emission becomes optically thin and follows $I_\nu \propto \nu^{-0.1}$, where the intensity remains nearly constant. Figure 1.9 illustrates how the spectral profile of HII regions evolves as they expand from HCHII regions to compact HII regions. The turnover frequency is defined as the frequency at which the emission becomes optically thin (i.e., $\tau = 1$). As an HII region expands, its electron density decreases, causing the turnover frequency (ν_t) to shift to lower frequencies. This shift occurs because the ionised gas exerts thermal pressure, driving expansion and reducing opacity as described in the previous section. SED profiles are crucial for characterizing HII regions at different evolutionary stages, these models are discussed further in Section 2.1.3.

As HII regions evolve, they pass through different observational stages, each with distinct properties. The earliest stages are hypercompact HII (HCHII) and ultracompact HII (UCHII) regions. HCHII regions are the youngest and most compact, with diameters of ≤ 0.05 pc, electron densities of $\geq 10^5$ cm $^{-3}$, and emission measures exceeding 10^8 pc cm $^{-6}$. They often exhibit broad radio recombination line (RRL) widths of $\Delta V \geq 40$ km s $^{-1}$, a sign of turbulent motion within the ionised gas (Kurtz, 2005a). UCHII regions represent the next stage, slightly larger with diameters up to 0.1 pc, electron densities of $\geq 10^4$ cm $^{-3}$, and emission measures of at least 10^7 pc cm $^{-6}$. Their RRL widths are narrower, around $\Delta V \sim 25$ – 30 km s $^{-1}$ (Churchwell, 2002).

As the ionised region continues to expand, it evolves into the compact HII and eventually the classical HII region phase. Classical HII regions are much larger, spanning several parsecs, with electron densities of $\sim 10^2$ – 10^3 cm $^{-3}$ and emission measures of $\sim 10^5$ – 10^6 pc cm $^{-6}$. Their RRL widths are typically $\Delta V \sim 20$ km s $^{-1}$. Unlike HCHII and UCHII regions, which are mainly detected at radio and infrared wavelengths, classical HII regions can also be seen in optical light due to their lower opacity.

Each of these evolutionary stages is characterised by different turnover frequencies, which directly influence their detectability. HCHII regions remain optically thick below 20 GHz, meaning they are primarily detectable at higher frequencies. UCHII regions, on the other hand, exhibit a turnover at around 5 GHz, transitioning from

optically thick to optically thin, with their SED becoming flat above this frequency. Compact HII regions, being more evolved, are optically thin at even lower frequencies and can be detected below 5 GHz.

The high optical depth of HC HII regions at low radio frequencies are therefore difficult to detect. Large-scale surveys such as CORNISH, THOR, and GLOSTAR, conducted between 1.4 GHz and 8 GHz, are effective at identifying UC HII and compact regions but are less sensitive to HC HII regions. As a result, detections of these early-stage HII regions remain elusive. High-frequency observations, which probe optically thin gas and capture the emission from small-scale structures, are essential for reliably detecting and characterizing HC HII regions.

Prior to the work presented in this thesis, only 23 HC HII regions had been identified (Yang et al. 2019; Yang et al. 2021 and references therein) and most of these have been serendipitously detected during high-frequency radio observations towards known UC HII regions. The current sample is therefore limited in number, and the manner in which its members have been identified, means that they may not be fully representative of this stage in the evolution of HII regions. Consequently, this limits our understanding of their properties and makes it difficult to constrain theoretical models for the early evolution of massive stars. It is therefore crucial to increase the sample size of HC HII regions, and to do this in a way that avoids relying on low-frequency radio surveys to identify candidates, which are likely to result in a bias to very bright and/or more evolved HC HII regions.

1.4 SCOTCH

The small number of known HC HII regions, together with potential observational biases in their identification, limits the ability to perform statistical studies of this important evolutionary stage. The Search for Clandestine Optically Thick Compact HII Regions (SCOTCH) was designed to address these limitations by systematically identifying new HC HII regions and refining our understanding of their role within the

broader context of high-mass star formation.

The SCOTCH survey was developed with three primary objectives:

- To increase the number of known HC HII regions and characterise their physical properties through high-frequency radio continuum observations;
- To construct a more representative sample of young compact HII regions by targeting methanol masers, which are established tracers of the early stages of high-mass star formation;
- To investigate the evolutionary relationship between HC HII, UC HII, and compact HII regions within the framework of massive star formation.

To identify a large and relatively unbiased sample of candidate young HII regions, SCOTCH targets 6.7 GHz class II methanol masers. These masers are radiatively pumped by strong mid-infrared emission from massive young stellar objects (MYSOs) (Cragg et al., 1992) and are well-established tracers of deeply embedded high-mass star formation (Breen et al., 2013). Observational studies indicate that methanol masers typically appear after the onset of the molecular outflow phase, once accretion onto the protostar generates sufficient luminosity to heat the surrounding envelope (Urquhart et al. 2022; Billington et al. 2019b; see Fig. 1.5).

Studies by Nguyen et al. (2022) suggest that approximately 12 per cent of methanol masers are associated with compact radio continuum emission, indicating that the methanol maser phase overlaps with the earliest stages of HII region evolution. As the ionised region expands beyond ~ 0.1 pc and transitions into the UC HII region phase, the masers are disrupted (Kurtz & Hofner, 2005). Methanol masers therefore provide an efficient means of selecting young and deeply embedded compact HII regions without relying on low-frequency radio continuum surveys, which are biased towards brighter and more evolved sources.

The most complete census of 6.7 GHz methanol masers is provided by the Methanol Multibeam (MMB) survey (Green, 2009). The MMB survey systematically mapped the Galactic plane ($60^\circ \geq \ell \geq 186^\circ$, $|b| < 2^\circ$) using the Parkes 64 m radio telescope. Follow-up observations with the Australia Telescope Compact Array (ATCA)

TABLE 1.3: Summary of the MMB survey papers and the number of 6.7 GHz methanol maser sites detected in each Galactic longitude range. The total number of maser sites detected is 972 between $186^\circ \leq \ell \leq 60^\circ$.

Galactic Longitude Range	Number of Maser Sites	Reference
$345^\circ \leq \ell \leq 6^\circ$	183	Caswell (2010)
$6^\circ \leq \ell \leq 20^\circ$	119	Green et al. (2010)
$330^\circ \leq \ell \leq 345^\circ$	198	Caswell et al. (2011)
$186^\circ \leq \ell \leq 330^\circ$	207	Green et al. (2012)
$20^\circ \leq \ell \leq 60^\circ$	265	Breen et al. (2015)

and the Multi-Element Radio Linked Interferometer Network (MERLIN) refined the source positions to sub-arcsecond accuracy. In total, the survey identified 972 methanol maser sites, representing the majority of known 6.7 GHz methanol masers in the Galaxy (Green et al., 2009). A summary of the MMB survey papers is provided in Table 1.3.

To confirm that the methanol masers are embedded within dense star-forming environments and to derive the physical properties of their natal clumps, the MMB catalogue was cross-matched with the ATLASGAL survey (Schuller et al., 2009). ATLASGAL is one of the largest and most sensitive submillimetre surveys of the Galactic plane, mapping thermal dust emission at $870\ \mu\text{m}$ across 420 square degrees. The survey covers Galactic longitudes from 60° to 280° and Galactic latitudes within $|b| < 1.5^\circ$, cataloguing more than 10,000 dense molecular clumps (Contreras et al., 2013; Csengeri et al., 2014; Urquhart et al., 2014c).

The physical properties of these clumps were derived by Urquhart et al. (2018) using multi-wavelength continuum data from the Herschel HiGAL survey (Molinari et al., 2010b). Spectral energy distribution (SED) fitting was used to determine dust temperatures and bolometric luminosities, from which clump masses, radii, luminosities, and column densities were calculated.

Distances to the ATLASGAL clumps were also adopted from Urquhart et al. (2018). Radial velocities relative to the local standard of rest (v_{LSR}) were obtained from molecular line observations using tracers such as CO, NH_3 , and N_2H^+ (see Table 1 of Urquhart et al. 2018). These velocities were combined with Galactic rotation models to derive kinematic distances where direct measurements were unavailable. For sources located within the Solar circle, the measured radial velocity corresponds to two possible heliocentric distances, known as the near and far kinematic distance ambiguity

(KDA). This ambiguity was resolved using several independent techniques, including H I absorption against radio continuum emission, H I self-absorption, associations with infrared dark clouds, and maser parallax measurements where available.

The resulting distances were subsequently used to derive the physical properties of the ATLASGAL clumps and are adopted throughout this thesis when calculating distance-dependent parameters such as physical size, luminosity, and Lyman-continuum photon flux. Typical uncertainties in the derived kinematic distances arise from non-circular motions and uncertainties in the adopted Galactic rotation model. Unless otherwise stated, all distances and distance-dependent physical parameters presented throughout this thesis are taken from Urquhart et al. (2018).

Each ATLASGAL clump was further classified into one of four evolutionary categories; quiescent, protostellar, young stellar object (YSO), or HII region, based on its infrared and radio properties (König et al., 2017). These classifications provide an additional means of assessing the evolutionary stage of the SCOTCH targets and help isolate the youngest and most compact regions.

Once the MMB–ATLASGAL associations were established, the resulting sample was targeted with high-frequency radio continuum observations to search for compact HII regions. SCOTCH primarily focuses on the southern Galactic plane, where archival ATCA observations were already available for 141 MMB methanol masers (Titmarsh et al., 2014, 2016). The analysis and results of these archival data are presented in Chapter 3. The compact radio continuum sources identified in that chapter are treated as candidate HC HII regions and are subsequently followed up with high-resolution observations in Chapter 4 to confirm their nature.

In Chapter 5, the methodologies developed in Chapters 3 and 4 are extended to a larger and previously unexplored sample of methanol masers in the fourth quadrant of the Galaxy. By combining both low- and high-resolution observations, this work aims to significantly increase the number of known HC HII regions and provide a more comprehensive analysis of their physical properties and evolutionary behaviour.

The next chapter provides an overview of the underlying physics of massive star formation and the emission mechanisms associated with HII regions. It outlines

the methods used to derive physical parameters from radio continuum observations, describes SED modelling techniques, and introduces the principles of radio interferometry, with particular focus on ATCA observations. The chapter concludes with a discussion of the calibration, imaging, and analysis procedures used throughout this thesis.

CHAPTER 2

THEORY

This chapter introduces the theoretical background of HII regions and massive star formation, providing an overview of the primary emission mechanisms and the derivation of key physical parameters. A summary of radio interferometry and the ATCA is then presented, outlining the observational procedures, data reduction, and imaging techniques. The chapter concludes with a detailed introduction to the data reduction methodology and the tools employed to ensure data quality and reliability.

2.1 TYPES OF EMISSION MECHANISMS

Within the ISM, radiation mechanisms can be broadly categorised into two types: spectral line emission and continuum emission. The following section provides a brief overview of these mechanisms.

Spectral Line Emission

Spectral line emission occurs when atoms or molecules undergo transitions between quantised energy levels, emitting radiation at specific wavelengths. The primary mechanisms responsible for this type of emission are electronic, vibrational, and rotational transitions.

Electronic transitions involve the movement of an electron between energy levels within an atom. When an electron drops from a higher to a lower energy level, electromagnetic radiation is emitted, with the wavelength determined by the energy difference between the two levels. In the presence of an external radiation field, atoms can also absorb photons, leading to the formation of absorption features in the spectrum. In ionised regions like HII regions, recombination between free protons and electrons occurs if the temperature is sufficiently low. During recombination, free electrons cascade from high quantum states (e.g., $n > 200$) towards the ground state; these are known as radio recombination lines (RRLs). These high quantum numbers correspond to energy differences that result in photon emissions within the 1-20 GHz frequency range, making radio observations ideal for detecting RRLs in ionised regions.

Vibrational transitions occur due to changes in the vibrational energy of molecules, specifically the stretching or bending of bonds between atoms. As the nuclei oscillate around their equilibrium positions, energy is released, often in the infrared part of the spectrum. This scenario is based on a simple molecule consisting of two atoms. For complex molecules, however, the situation becomes more complicated due to the presence of multiple vibrational modes, interactions between these modes, and anharmonic effects. These anharmonic effects occur when the bond vibrations deviate from the ideal spring-like behaviour, resulting in a more intricate energy level structure and more complex absorption patterns.

Rotational transitions are caused by changes in a molecule's angular momentum. As a molecule transitions between different rotational energy states, photons may be emitted or absorbed, depending on whether the transition leads to an increase or decrease in energy. This results in distinct spectral lines at specific frequencies, commonly found in the microwave and radio portions of the spectrum.

Continuum emission

Continuum emission can be split into two types: thermal blackbody dust emission and bremsstrahlung radiation also known as free-free radiation. Blackbody radiation refers to the thermal motion of dust grains and radiates at all wavelengths. Thermal radiation has a continuous spectrum that is temperature-dependent. Hotter objects emit more intense radiation and peak at a specific wavelength as described by Planck's law. Thermal blackbody radiation is usually the dominant mechanism in the ISM, however at lower frequencies (i.e., < 20 GHz), bremsstrahlung emission can dominate. The radiation emerges from the interaction between electrons and atomic nuclei within the presence of an electric field.

2.1.1 RADIO CONTINUUM EMISSION

Radio continuum emission can be broken into two primary mechanisms: thermal bremsstrahlung (free-free) and non-thermal (synchrotron) emission. These processes are fundamentally distinguished by their physical conditions and dependence on temperature and magnetic fields, respectively.

Thermal Bremsstrahlung

Thermal bremsstrahlung, or free-free emission, is the dominant emission mechanism in ionised regions, such as HII regions. It occurs when free electrons are decelerated by interactions with positive ions, transferring kinetic energy that is emitted as radio continuum radiation. As an electron is deflected by a positively charged ion, it accelerates and emits radio photons, as illustrated in Fig. 2.1. The strength of thermal free-free emission depends on three key factors: temperature, electron density, and optical depth. The temperature of the ionised gas determines the average kinetic energy of the electrons, with higher temperatures leading to higher energy collisions between electrons and ions. Although faster-moving electrons may reduce the frequency of collisions by spending less time near ions, each collision tends to release more energy. The electron density plays a crucial role by increasing the likelihood of collisions, thereby

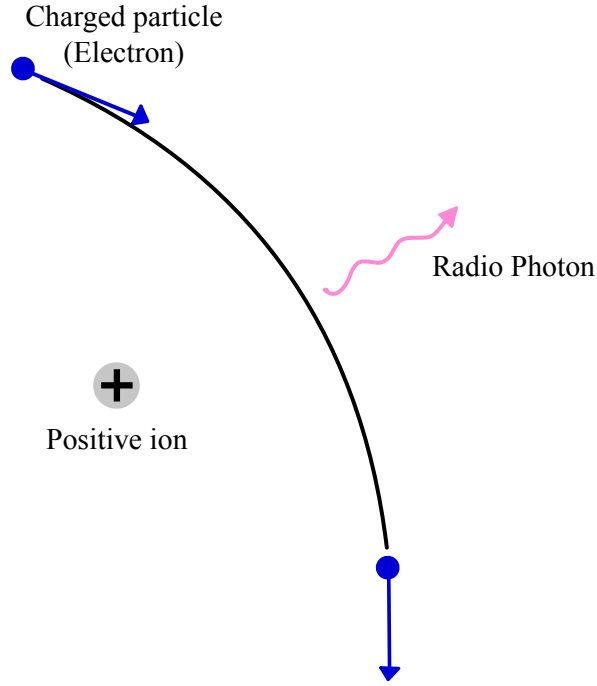


FIGURE 2.1: Schematic representation of thermal bremsstrahlung emission, illustrating the interaction between an electron and a positively charged ion, with the resulting emission of radio photons.

enhancing the overall emission. Finally, the optical depth of the ionised region determines whether the emitted radiation escapes or is absorbed, affecting the strength of the observed emission.

Non-Thermal Bremsstrahlung

Non-thermal emission, or synchrotron radiation, occurs when highly relativistic electrons spiral along magnetic field lines, emitting radiation as they are accelerated, as illustrated in Fig. 2.2. The strength of this emission is influenced by the magnetic field and the energy of the electrons. As electrons travel along curved paths, they lose energy in the form of radio photons. Unlike thermal bremsstrahlung, which depends on temperature, synchrotron radiation is primarily governed by the magnetic field and the velocity of the electrons.

Synchrotron radiation produces a broad spectrum, typically showing a decrease in intensity at higher frequencies. It is commonly found in environments with strong magnetic fields, such as supernova remnants, pulsar wind nebulae, and extragalactic

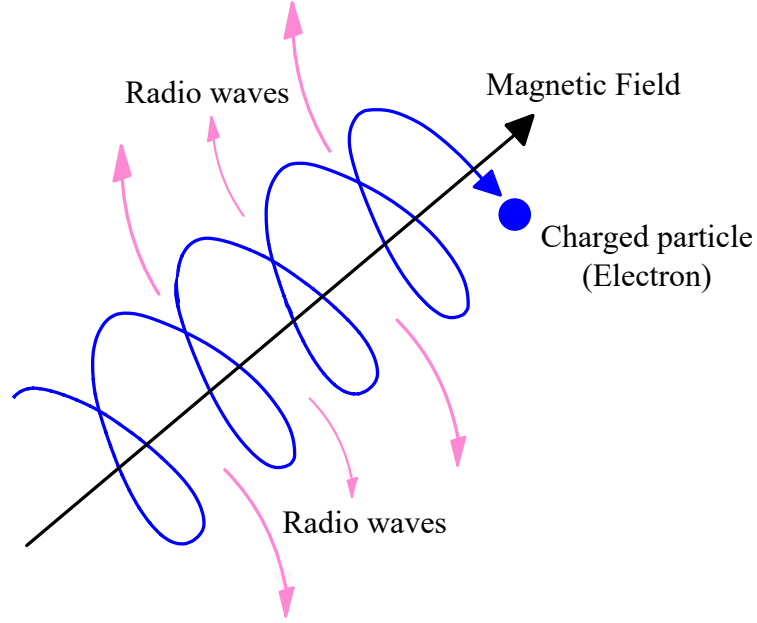


FIGURE 2.2: Schematic representation of synchrotron emission, showing the spiral motion of an electron around a magnetic field line and the resulting emission of radio waves.

sources like active galactic nuclei (AGN), including quasars and radio galaxies.

2.1.2 DERIVING THE PHYSICAL PARAMETERS OF HII REGIONS

HII regions are characterised by ionised gas and weak magnetic fields, and are prominent sources of thermal bremsstrahlung emission. This emission, primarily at radio frequencies (1-100 GHz), highlights the thermal nature of the ionised gas (Beuther et al., 2010). Unlike sources dominated by synchrotron radiation, HII regions are not strongly influenced by magnetic fields as their weak magnetic field strengths (on the order of a few microgauss) are overpowered by the thermal pressure of the ionised gas, which plays a dominant role in shaping their dynamics (Heiles & Troland, 2005). In this section, we will derive the equations that enable us to calculate the physical parameters of HII regions. This will form the foundation of our analysis throughout this thesis.

Radiative transfer

Thermal emitters in the interstellar medium are in thermal equilibrium and can be described as a blackbody, governed by Planck's law:

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1}, \quad (2.1)$$

where h is the Planck constant ($6.63 \times 10^{-34} \text{ m}^2 \text{ kg s}^{-1}$) and c is the speed of light ($3 \times 10^8 \text{ m s}^{-1}$). Almost everything we know about the universe comes from the study of electromagnetic radiation. At radio wavelengths, the intensity of a source, or brightness (I_ν), can be defined by the following equation:

$$dP = I_\nu \cos \theta d\Omega d\sigma d\nu, \quad (2.2)$$

where dP is the infinitesimal power (W), $d\sigma$ is the infinitesimal source area (m^2), $d\nu$ is the infinitesimal bandwidth (Hz), θ is the angle between the normal to $d\sigma$ and the direction of $d\Omega$ (sr). The intensity I_ν , is independent of the distance between the source and observer and is a fundamental quantity that describes the energy transmitted or received per second, per unit area, per unit solid angle, and per unit frequency ($\text{W m}^{-2} \text{sr}^{-1} \text{Hz}^{-1}$). By integrating the full intensity of a source that subtends some solid angle on the sky ($d\Omega$), we get the total intensity of the source:

$$S_\nu = \int_{\Omega_s} I_\nu(\theta, \phi) \cos \theta d\Omega, \quad (2.3)$$

The solid angle of a source, Ω , is a dimensionless unit, measured in steradians (sr). For a circular source, the solid angle can be expressed as $\Omega = \alpha \theta_{\text{FWHM}}^2$, where α is a constant that depends on the source's structural model (e.g., Gaussian, cylindrical, or spherical; Mezger & Henderson 1967). The total intensity of a source is also known as flux density, which is equal to the intensity integrated over the solid angle $d\Omega$:

$$S_\nu = \int I_\nu d\Omega. \quad (2.4)$$

The SI unit of flux density is $\text{W m}^{-2} \text{Hz}^{-1}$. However, because many astronomical objects have much lower flux densities, astronomers typically use a smaller unit called

the Jansky, defined as:

$$1 \text{ Jansky} = 1 \text{ Jy} \equiv 10^{-26} \text{ W m}^{-2} \text{ Hz}^{-1}. \quad (2.5)$$

As we mentioned earlier, the intensity of radiation remains independent of the distance between the source and the observer. However, in reality the intensity will change if the radiation is absorbed or emitted. These mechanisms can be described by the equation of radiative transfer:

$$\frac{dI_\nu}{ds} = j_\nu - \kappa_\nu I_\nu, \quad (2.6)$$

where j_ν and κ_ν represent the emission and absorption coefficients, respectively. The equation of radiative transfer quantifies how the intensity of radiation, I_ν , changes along a path s due to emission and absorption. The balance between these processes determines the net change in intensity. For HII regions, we can assume the gas is in thermodynamic equilibrium (TE), meaning the electrons and ions have a temperature defined energy distribution and collide often enough that the gas stays close to equilibrium. Under this assumption, the radiative transfer equation has the solution:

$$\frac{dI_\nu}{ds} = 0, \quad I_\nu = B_\nu(T) = \frac{j_\nu}{\alpha_\nu}. \quad (2.7)$$

In TE, the spectral energy distribution of a source is described by the Planck function $B_\nu(T)$ at a temperature T in K:

$$B_\nu(T) = \frac{2kT\nu^2}{c^2}. \quad (2.8)$$

This equation can be rewritten to express ν from the Planck function in GHz:

$$B_\nu(T) = 3.068 \times 10^{-22} \left(\frac{\nu}{\text{GHz}} \right)^2 \left(\frac{T}{\text{K}} \right). \quad (2.9)$$

Kirchhoff's law of thermal radiation states that the Planck function is equivalent to the ratio of the emissivity, j_ν , and absorption coefficient, α_ν . Another important factor that influences the absorption coefficient is the optical depth. The optical depth, τ_ν ,

is a dimensionless quantity that quantifies the transparency of a medium to radiation at a specific frequency, ν . It is defined as the integral of the absorption coefficient, κ_ν , along the line of sight, s :

$$d\tau_\nu = \kappa_\nu ds. \quad (2.10)$$

The equation of radiative transfer can be expressed in terms of optical depth by substituting Eq. 2.10 into Eq. 2.6 and then dividing both sides by κ_ν , resulting in:

$$\frac{dI_\nu}{d\tau_\nu} = I_\nu - \frac{j_\nu}{\alpha_\nu} = B_\nu(T) - I_\nu, \quad (2.11)$$

Assuming that T is constant throughout the nebula, $I_\nu = 0$ at $\tau_\nu = 0$, the solution to the above equation from Rybicki & Lightman 1986 is:

$$I_\nu = B_\nu(T) (1 - e^{-\tau_\nu}), \quad (2.12)$$

which has two limiting factors, in the case:

$$I_\nu = \begin{cases} B_\nu \tau_\nu & \text{if } \tau_\nu \ll 1 \quad (\text{Optically thin}) \\ B_\nu & \text{if } \tau_\nu \gg 1 \quad (\text{Optically thick}). \end{cases} \quad (2.13)$$

The equations derived above describe thermal emission in general. We now apply these principles to HII regions, where free-free radiation plays a dominant role. From Mezger & Henderson (1967) the optical depth τ of free-free radiation is defined by:

$$\tau_\nu = 8.235 \times 10^{-2} \left(\frac{T_e}{\text{K}} \right)^{-1.35} \left(\frac{\nu}{\text{GHz}} \right)^{-2.1} \left(\frac{EM}{\text{pc cm}^{-6}} \right), \quad (2.14)$$

where T_e is the electron temperature ν is the frequency, and EM is the emission measure. For an optically thin nebula, the intensity of the source is given by:

$$I_\nu = B_\nu \tau_\nu. \quad (2.15)$$

Substituting for Eq. 2.9 and Eq. 2.14, and converting the flux into Jansky this becomes:

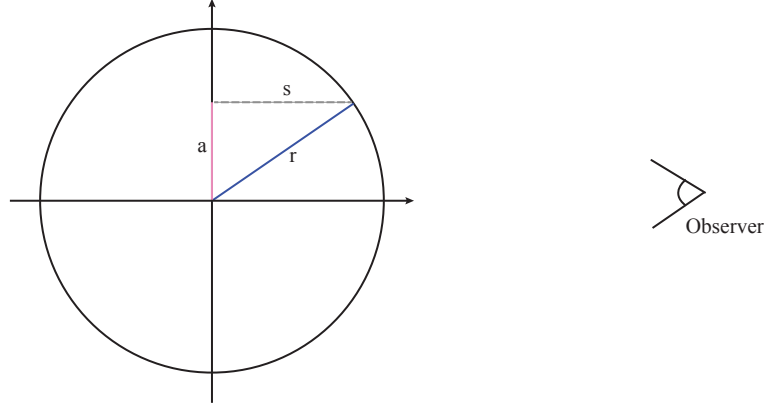


FIGURE 2.3: Simple schematic of a spherical HII region. From the observer's perspective, r is the physical radius of the region, a is the projected distance from the centre on the plane of the sky, and $s = \sqrt{r^2 - a^2}$ is the half-path length through the sphere along the line of sight. The emission measure is obtained by integrating n_e^2 over the full line-of-sight path.

$$\left(\frac{I_\nu}{\text{Jy}}\right) = 2.525 \times 10^3 \left(\frac{T_e}{\text{K}}\right)^{-0.35} \left(\frac{\nu}{\text{GHz}}\right)^{-0.1} \left(\frac{EM}{\text{pc cm}^{-6}}\right). \quad (2.16)$$

Flux Density and Geometry

In this analysis, we consider HII regions as Strömgren spheres. They are fully ionised regions and contain no dust. Figure 2.3 illustrates a simplified representation of an HII region, where the electron density, n_e , is assumed to be constant within a radius r . To evaluate the total flux density within a given circular aperture, we calculate the solid angle subtended by the source using the following:

$$\Omega_{\text{source}} = 2\pi \int_0^{\theta_0} \theta_a \psi(\theta_a) d\theta_a, \quad (2.17)$$

where $\psi(\theta_a)$ describes the intensity distribution of the source as a function of angular position θ_a . For a circular source with uniform brightness, the solid angle can be simplified to:

$$\Omega_{\text{source}} = \frac{\pi}{6} \theta_{\text{source}}^2, \quad (2.18)$$

where θ_{source} is the angular diameter of the source in radians. Expressing this in arcsec, we have:

$$\Omega_{\text{source}} = 1.231 \times 10^{-11} \left(\frac{\theta_{\text{source}}}{\text{arcsec}} \right)^2. \quad (2.19)$$

Combining Eq. 2.19 with Eq. 2.16 we can express the flux density as:

$$\left(\frac{S_\nu}{\text{Jy}} \right) = 3.11 \times 10^{-8} \left(\frac{T_e}{\text{K}} \right)^{-0.35} \left(\frac{\nu}{\text{GHz}} \right)^{-0.1} \left(\frac{EM}{\text{pc cm}^{-6}} \right) \left(\frac{\theta_{\text{source}}}{\text{arcsec}} \right)^2. \quad (2.20)$$

Emission Measure and Electron density

The emission measure represents the total number of free electrons and protons along the line of sight, per unit area, giving a measure of how much ionised gas the radiation passes through. Equation 2.20 is fundamental to our analysis, as it serves as the basis for deriving the emission measure and electron density of HII regions. By rearranging the terms we are able to determine the emission measure (EM):

$$\left(\frac{EM}{\text{pc cm}^{-6}} \right) = 3.217 \times 10^7 \left(\frac{S_\nu}{\text{Jy}} \right) \left(\frac{T_e}{\text{K}} \right)^{0.35} \left(\frac{\nu}{\text{GHz}} \right)^{0.1} \left(\frac{\theta_{\text{fwhm}}}{\text{arcsec}} \right)^{-2} \quad (2.21)$$

The EM can be defined as the integral of the number of electrons and number of ions along the line-of-sight. EM is usually expressed as:

$$EM = 2 \int_0^{s'} n_e n_p ds, \quad (2.22)$$

where the factor of 2 accounts for both sides of the sphere, n_e and n_p are the electron and proton densities and ds is the radius of the HII region along the line of sight. Assuming that there is an equal number of electrons and protons, the equation simplifies to:

$$EM = 2n_e^2 \int_0^{s'} ds. \quad (2.23)$$

Since the electron density is uniform within the HII region, we can rewrite the equation

above taking into account the geometry from Fig. 2.3 where $s = \sqrt{r^2 - a^2}$:

$$EM = 2n_e^2 \sqrt{r^2 - a^2}. \quad (2.24)$$

We can simplify this further by taking the r outside the square-root and dividing everything in the square-root by r :

$$EM = 2n_e^2 r \sqrt{1 - \frac{a^2}{r^2}}. \quad (2.25)$$

The radius of the HII region on the sky can be described by an angle, θ_r , and the distance to the source D :

$$r = D\theta_r. \quad (2.26)$$

The ratio of the lengths a and r is the same as the ratio of the angular sizes (since $r = D\theta_r$ and $a = D\theta_a$). The above equation therefore becomes:

$$EM = 2n_e^2 D\theta_r \sqrt{1 - \left(\frac{\theta_a}{\theta_r}\right)^2}. \quad (2.27)$$

The maximum emission measure occurs at the centre of the HII region ($a = 0$), where the square-root term = 1. At this point, the source diameter is defined as $\theta_d = 2\theta_r$, and Eq. 2.27 simplifies to:

$$EM = n_e^2 D\theta_d. \quad (2.28)$$

Converting θ_d from radians to arcseconds gives:

$$\left(\frac{EM}{\text{pc cm}^{-6}}\right) = \frac{1}{206265} \left(\frac{n_e}{\text{cm}^{-3}}\right)^2 \left(\frac{D}{\text{pc}}\right) \left(\frac{\theta_d}{\text{arcsec}}\right). \quad (2.29)$$

Substituting the above into Eq. 2.21, we have:

$$\frac{n_e^2 D\theta_d}{206265} = 3.217 \times 10^7 \left(\frac{S_\nu}{\text{Jy}}\right) \left(\frac{T_e}{\text{K}}\right)^{0.35} \left(\frac{\nu}{\text{GHz}}\right)^{0.1} \left(\frac{\theta_d}{\text{arcsec}}\right)^{-2}. \quad (2.30)$$

This equation can now be rearranged to determine the electron density of the HII region:

$$n_e = 2.576 \times 10^6 \left(\frac{S_\nu}{\text{Jy}} \right)^{0.5} \left(\frac{T_e}{\text{K}} \right)^{0.175} \left(\frac{\nu}{\text{GHz}} \right)^{0.05} \left(\frac{\theta_d}{\text{arcsec}} \right)^{-1.5} \left(\frac{D}{\text{pc}} \right)^{-0.5}. \quad (2.31)$$

Lyman Continuum Flux

The Lyman continuum photon flux, N_{Ly} , can be derived by balancing the rates of recombinations and photoionisations within an HII region. Using the Strömgren sphere model, this balance is expressed as:

$$N_{\text{Ly}} = \frac{4}{3} \pi \left(\frac{r_s}{\text{cm}} \right)^3 \left(\frac{n_e}{\text{cm}^{-3}} \right)^2 \left(\frac{\beta - \beta_1}{\text{cm}^3 \text{s}^{-1}} \right), \quad (2.32)$$

where r_s is the Strömgren radius n_e is the electron density, and $(\beta - \beta_1)$ represents the effective recombination coefficient for all energy levels except the ground state. Here, β is the total recombination coefficient, while β_1 is the recombination coefficient to the ground state. Rubin (1968) approximated this coefficient for an electron temperature of $T_e = 10^4 \text{ K}$ in HII regions as:

$$\beta - \beta_1 \approx 4.1 \times 10^{-10} T_e^{-0.8} \text{ cm}^3 \text{s}^{-1}. \quad (2.33)$$

The Strömgren radius can be converted to the angular diameter if the distance to the HII region is known:

$$r_s = \frac{1}{2} \left(\frac{\theta_d}{\text{rad}} \right) \left(\frac{D}{\text{cm}} \right), \quad (2.34)$$

where θ_d is the angular diameter and D is the distance. Converting the angular size from radians to arcseconds and the distance from cm to parsecs, the radius becomes:

$$r_s = 1.53 \times 10^{18} \left(\frac{D}{\text{pc}} \right) \left(\frac{\pi}{648000} \right) \left(\frac{\theta_d}{\text{arcsec}} \right). \quad (2.35)$$

Combining these expressions, the Lyman continuum photon flux becomes:

$$N_{\text{Ly}} = 1.935 \times 10^{45} \times \left(\frac{D}{\text{pc}}\right)^3 \times \left(\frac{\pi}{648000}\right)^3 \times \left(\frac{\theta_d}{\text{arcsec}}\right)^3 \times \left(\frac{n_e}{\text{cm}^{-3}}\right)^2 \times \left(\frac{T_e}{\text{K}}\right)^{-0.8}. \quad (2.36)$$

Simplifying further:

$$N_{\text{Ly}} = 6.93 \times 10^{29} \left(\frac{D}{\text{pc}}\right)^3 \left(\frac{\theta_d}{\text{arcsec}}\right)^3 \left(\frac{n_e}{\text{cm}^{-3}}\right)^2 \left(\frac{T_e}{\text{K}}\right)^{-0.8}. \quad (2.37)$$

Substituting the expression for the electron density, Eq. 2.31 into the equation above, we obtain:

$$N_{\text{Ly}} = 6.93 \times 10^{29} \times (2.576 \times 10^6)^2 \left(\frac{S_\nu}{\text{Jy}}\right) \left(\frac{T_e}{\text{K}}\right)^{-0.45} \left(\frac{\nu}{\text{GHz}}\right)^{0.1} \left(\frac{D}{\text{pc}}\right)^2, \quad (2.38)$$

Assuming $T_e = 10,000 \text{ K}$, the final expression becomes:

$$N_{\text{Ly}} = 7.3 \times 10^{40} \left(\frac{S_\nu}{\text{Jy}}\right) \left(\frac{\nu}{\text{GHz}}\right)^{0.1} \left(\frac{D}{\text{pc}}\right)^2, \quad (2.39)$$

Turnover Frequency

The optical depth measures how transparent or opaque the ionised gas is to radiation. When the optical depth (Eq. 2.14) $\tau_\nu = 1$, this frequency is known as the turnover frequency ν_t . At this frequency, the ionised gas transitions from being optically thick (at lower frequencies) to optically thin (at higher frequencies). The turnover frequency can be expressed as:

$$\left(\frac{\nu_t}{\text{GHz}}\right) = 0.3045 \left(\frac{T_e}{10^4 \text{ K}}\right)^{0.643} \left(\frac{EM}{\text{cm}^{-6} \text{ pc}}\right)^{0.476} \quad (2.40)$$

These equations provide reliable estimates when the emission is optically thin. If the emission remains optically thick at the observing frequency, the derived quantities should be treated with caution, and multi-frequency SED modelling is required to better constrain the physical parameters. A more detailed discussion is presented in Chapter 4 and 5.

2.1.3 SED MODELLING

The equations presented in the previous section provide one method for determining the physical parameters of HII regions by using a single radio flux density measurement. Another approach for determining the physical parameters of HII regions involves modelling radio flux densities across multiple frequencies to capture the characteristic spectral shape arising from free-free emission (see Fig. 1.9). In this thesis, we apply both approaches to derive these properties, depending on the data suitability. While both approaches are discussed in detail in later chapters, this section provides an overview of the practical application of the model spectral energy distributions (SEDs) used to estimate the diameter, electron density, and emission measure.

The radio-frequency spectrum of an HII region is primarily shaped by free-free interactions between electrons and ions in the ionised gas, producing continuum emission across a broad range of frequencies. This emission is governed by the electron temperature (T_e) and the emission measure ($EM = n_e^2 d$), which quantify the density and depth of the ionised gas. By modelling the flux density across both optically thick and optically thin regimes, we can constrain key physical parameters such as electron density (n_e) and diameter. The resulting continuum spectrum follows the relation $S_\nu \propto T_e^{-0.35} EM$, reflecting the thermal properties of the HII region.

In this thesis, we employ two complementary methods to extract these properties, depending on the available data: (1) a multi-band SED fit to determine the physical properties; and (2) an analysis of the optically thin part of the SED to obtain the physical properties.

To model the radio emission of HII regions, we use our flux density measurements at 18 GHz and 24 GHz, supplemented with additional 5 GHz data where available in the literature. These multi-wavelength data allow us to construct SEDs for each HII region, providing insights into the region's structure and ionisation conditions. From Mezger & Henderson (1967) the integrated flux density S_ν at frequency ν for a typical HII region is given by:

$$S_\nu = \frac{2k\nu^2 \Omega T_e (1 - e^{-\tau})}{c^2}. \quad (2.41)$$

The SED fitting process involves fitting the observed flux densities at various frequencies to Eq. 2.41 to estimate two primary parameters: the electron density and the diameter of the region. This approach provides a means of capturing the optically thick and thin regimes of the free-free emission, each of which offers different insights into the physical properties of the ionised gas. While the SED fitting model is a powerful tool for estimating physical properties of HII regions, several assumptions have had to be made:

- **Spherical Symmetry and Homogeneity:** The model assumes a spherical, uniform density distribution, which simplifies the calculations but may not accurately represent the complex structures observed in real HII regions. Irregular morphologies, clusters, or shell-like structures may cause deviations from the idealised model. However, the majority of our sources are unresolved or only marginally resolved, meaning no detailed structural information is available. Therefore, assuming spherical symmetry and homogeneity is a reasonable and practical approximation for our analysis.
- **Constant Electron Temperature:** We assume a uniform electron temperature ($T_e = 10^4$ K) across the region. However, local variations in temperature, driven by processes such as photoionisation or radiative cooling, may impact the accuracy of this assumption, especially in larger or more evolved HII regions. Nevertheless, this value is consistent with the temperatures used in Khan et al. (2024), where most HII regions have temperatures of $T_e = 8000$ K. Given that our sources are compact and often unresolved, the assumption of a uniform $T_e = 10^4$ K remains a reasonable and widely accepted approximation.
- **Root-Mean-Square Electron Density:** The derived electron density represents a root-mean-square (rms) value averaged over the volume of the region. Since the majority of our sources are unresolved or only marginally resolved, this measurement reflects an integrated property rather than detailed spatial structure. As a result, it may not fully capture localised density variations or inhomogeneities within the ionised gas.

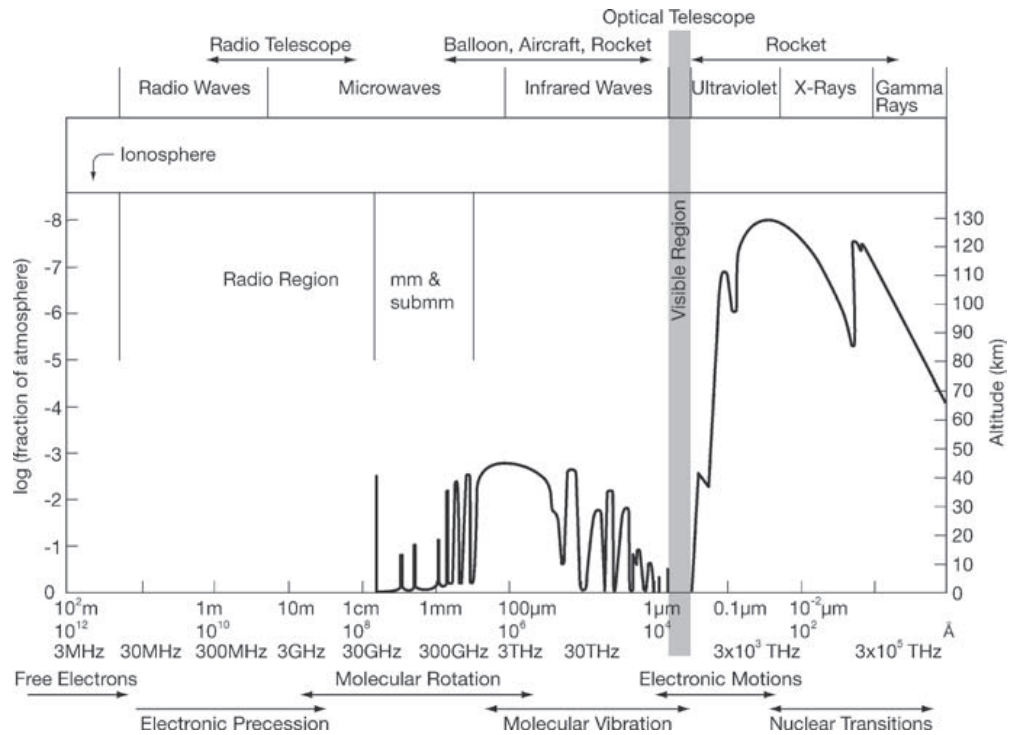


FIGURE 2.4: The transmission of electromagnetic radiation through Earth’s atmosphere is shown, with the vertical axis representing the altitude at which the radiation is reduced to 50% of its original intensity (Wilson et al., 2013).

2.2 INTERFEROMETRY

This thesis primarily uses data from radio observations in the centimetre and millimetre wavelength regimes. Radio astronomy began in the early 1930s, following the ground-breaking discovery of an extraterrestrial radio signal by Karl Jansky, an engineer at Bell Telephone Laboratories. His work marked the beginning of radio astronomy, opening up a new observational window and expanding our understanding of the universe.

2.2.1 THE RADIO WINDOW

The Earth’s atmosphere allows the transmission of certain portions of the electromagnetic spectrum, known as atmospheric windows, which enable ground-based telescopes to observe the universe. Two such windows correspond to the optical and radio bands. Regions of space that are opaque to higher-frequency waves, like visible light, are often transparent to radio waves. This range of transparency, known as the “radio

window,” spans frequencies from approximately 15 MHz to 600 GHz, corresponding to wavelengths from about 20 meters to 0.5 millimetres (see Fig. 2.4; Wilson et al. 2013).

Radio sources vary widely in angular size and surface brightness, requiring different approaches for specific observations. As a result, astronomers primarily rely on two types of radio telescopes: single-dish telescopes and aperture synthesis interferometers.

Single-dish telescopes, typically designed as parabolic reflectors, are the most common type of radio telescope. They provide large collecting areas and can observe a wide frequency range with high sensitivity. Incoming radio waves are reflected by the parabolic surface and focused onto a feed antenna for detection. The angular resolution of a single-dish telescope depends on its diameter (D) and the wavelength of the observed radiation (λ), expressed as:

$$\delta \sim \frac{\lambda}{D} \quad (2.42)$$

where δ represents the angular resolution in radians. Larger dish diameters improve both sensitivity and resolution, allowing faint sources to be detected and finer details to be resolved. However, structural and practical constraints limit the size of fully steerable single-dish telescopes to about 100 meters, such as the Green Bank Telescope.

Interferometers overcome these limitations by linking multiple smaller antennas into an array. Signals from these antennas are combined, effectively synthesizing the resolution of a much larger telescope. This technique, significantly enhances angular resolution and allows astronomers to study fine details of radio sources that single dishes cannot resolve.

2.2.2 OVERVIEW OF RADIO INTERFEROMETRY

Radio interferometry is a powerful technique that provides the high angular resolution and sensitivity required to study massive star-forming regions and to detect weak radio sources with low flux densities. Unlike single-dish telescopes, where the resolution is limited by the physical size of the dish, the resolution of an interferometer is determined by the maximum separation between its antennas, referred to as the baseline (B). In the simplest case of an interferometer, which consists of two antennas, the baseline is

the distance between the two elements, and this separation directly impacts the angular resolution of the telescope. The angular resolution, θ , measured in radians, is given by:

$$\theta \sim \frac{\lambda}{B}. \quad (2.43)$$

The antennas observe the same astronomical source simultaneously and in the same direction. The radiation, with frequency ν , is received by each telescope with a geometric time delay, τ_g , defined as:

$$\tau_g = \mathbf{b} \cdot \frac{\mathbf{s}}{c}, \quad (2.44)$$

where $\mathbf{b}$ is the baseline vector, $\mathbf{s}$ is the unit vector pointing toward the source, and c is the speed of light. Due to differences in path lengths, the signals must be coherently combined in a correlator, where they are aligned and processed through convolution. An interferometer measures the mutual coherence, V_ν , of an incoming electromagnetic wave at two antennas located at positions r_1 and r_2 . A simple schematic of an interferometer is shown in Fig. 2.5. This mutual coherence, also known as the spatial coherence function, is defined as:

$$V_\nu(r_1, r_2) = \int I_\nu(\mathbf{s}) e^{-2\pi i \mathbf{s} \cdot (\mathbf{r}_1 - \mathbf{r}_2)/c} d\Omega, \quad (2.45)$$

where $I_\nu(\mathbf{s})$ is the two-dimensional intensity distribution on the sky, $\mathbf{s}$ is the unit vector in the direction of the celestial source, $(\mathbf{r}_1 - \mathbf{r}_2)$ is the separation vector between antennas 1 and 2, and $d\Omega$ indicates the integration over the solid angle of the antenna beam.

The brightness distribution of an astronomical object is not measured directly. Instead, interferometric observations map a quantity known as the complex visibility, $V_\nu(u, v)$, which is a unique function of the source brightness. An interferometer records one visibility measurement at a time, corresponding to each baseline coordinate (u, v) as the Earth rotates. The 2D visibility function is defined as follows:

$$V_\nu(u, v) = \iint I_\nu(l, m) e^{-2\pi i (ul + vm)} dl dm. \quad (2.46)$$

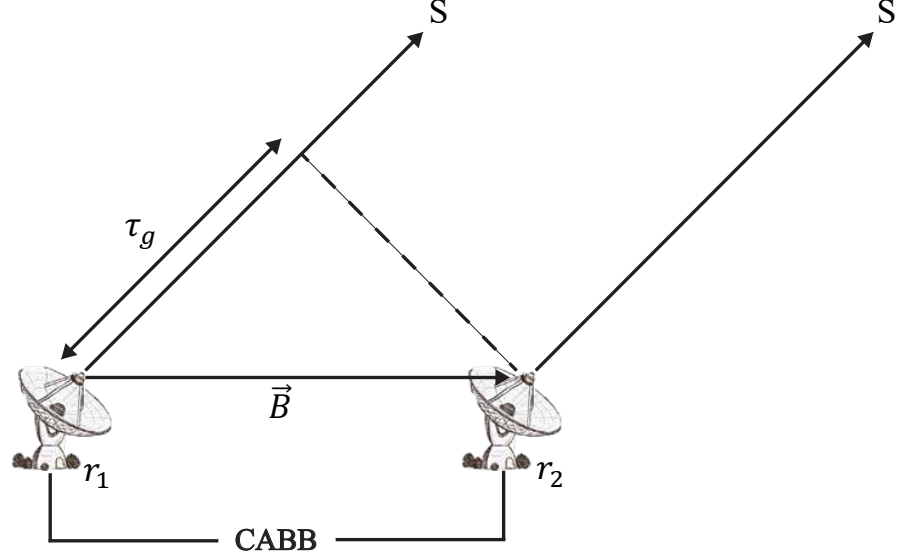


FIGURE 2.5: Diagram illustrating the interferometric setup with two radio antennas separated by baseline vector B , observing a distant signal source S . The signals received by the antennas at positions r_1 and r_2 have a geometric delay τ_g between them due to the difference in path lengths. The signal is processed by the Compact Array Broadband Backend (CABB; Wilson et al. 2011), which correlates the data from both antennas to measure the interference pattern.

In this equation, (l, m) represents the direction cosines of the point source on the sky, while (u, v) are the baseline coordinates of the interferometer. The sky intensity distribution, $I_\nu(l, m)$, can be obtained by inverting Eq. 2.46 through a Fourier transform, as described by the Van Cittert-Zernike theorem (Wilson et al., 2009). The relation between visibility and sky brightness is given by:

$$V_\nu(u, v) \xrightarrow{\mathcal{F}} I_\nu(l, m). \quad (2.47)$$

Thus, the sky brightness distribution can be expressed as:

$$I_\nu(l, m) = \iint V_\nu(u, v) e^{2\pi i(ul+vm)} du dv. \quad (2.48)$$

However, the equation above describes an idealized scenario where the spatial coherence function is fully sampled across the sky. In reality, only discrete points on the uv -plane are sampled by the interferometric baselines between antenna pairs, which can lead to gaps in the uv -coverage. To achieve an accurate sky brightness image, the

uv -plane must be well-sampled. For an array of N radio telescopes, there are $\frac{N(N-1)}{2}$ unique interferometric baselines, each providing visibilities that contribute to the image's resolution and accuracy. By observing over a longer time period, we can use the Earth's rotation to fill gaps in the uv -coverage. Figure 2.6 illustrates two examples: the top panel shows a target with complete hour angle coverage, while the bottom panel demonstrates a sparsely sampled uv -plane, typically resulting in lower-quality imaging.

These under-sampled gaps in uv -coverage produce a *dirty image* that is the convolution of the true image with the *dirty beam* given by:

$$I_{\nu,D}(l, m) = \iint V_{\nu}(u, v) S(u, v) e^{-2\pi i(ul+vm)} du dv. \quad (2.49)$$

In this equation, the sampling function $S(u, v)$ describes which parts of the $u - v$ plane contain measured data. For regions with no data, $S(u, v)$ assigns a zero, to mitigate the effect of missing data, which can contribute to sidelobes in the synthesized beam such that:

$$S(u, v)V(u, v) \xrightarrow{\mathcal{F}} I_{\nu,D}(l, m). \quad (2.50)$$

Thus, the observed intensity distribution $I_{\nu,D}(l, m)$ is the convolution of the true intensity $I_{\nu}(l, m)$ and the synthesized beam, $B(l, m)$:

$$I_{\nu,D}(l, m) = I_{\nu}(l, m) * B(l, m), \quad (2.51)$$

where the synthesized beam $B(l, m)$ can be expressed as:

$$B(l, m) = \iint S(u, v) e^{2\pi i(ul+vm)} du dv. \quad (2.52)$$

It is common to improve dirty images using deconvolution, especially when the field of view contains more than one unresolved source. A standard approach is to apply the CLEAN algorithm. This algorithm models the sky as a collection of point sources, defined by their peak intensity and position. It begins by identifying the brightest point in the dirty image, $I_D(l, m)$, and iteratively subtracting the peak intensity by

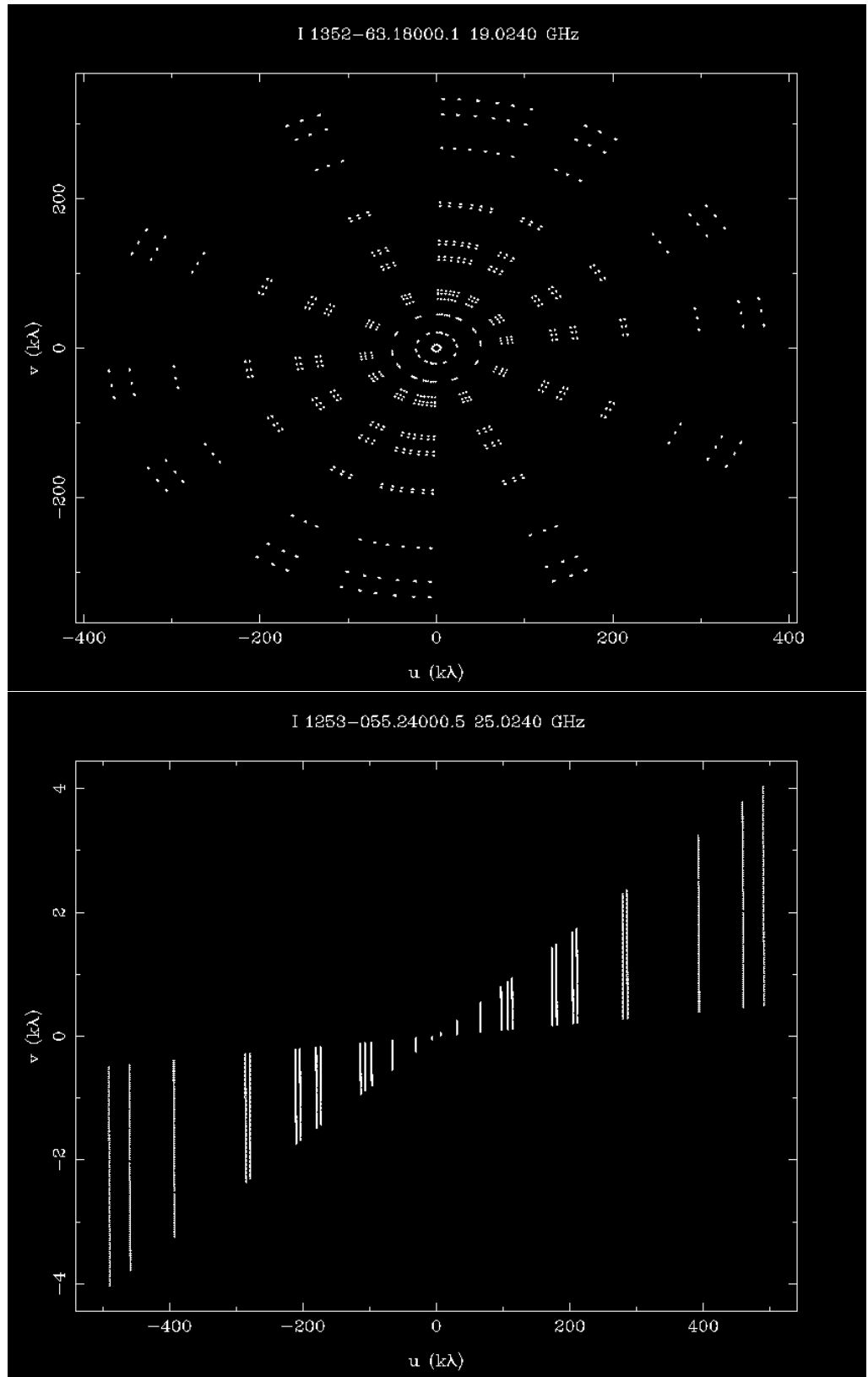


FIGURE 2.6: Comparison of uv -coverage for an observed object: the top panel depicts complete hour-angle coverage, while the bottom panel illustrates incomplete sampling.

scaling the dirty beam, $B(l, m)$, at each identified position. This subtraction continues until no further reduction is possible or until the first negative value appears in the dirty map. The subtracted intensities, called CLEAN components, are stored and later convolved with a restoring beam (or clean beam), typically an elliptical Gaussian fit to the central region of $B(l, m)$. This convolved image is added to the residual image, producing an estimate of the sky brightness distribution in units of Jy/beam.

2.2.3 OBSERVING PROCEDURE

When conducting interferometric observations we must take observations of a nearby unresolved point source ($\sim < 10^\circ$), which is referred to as the secondary, or phase, calibrator. Phase calibrators are an integral part of observations and are used to correct for instrumental effects and atmospheric fluctuations of the detected signal. Under good weather conditions you would ideally observe the phase calibrators once every 20 minutes when observing at 20 GHz, before and after each set of target sources.

Observations of the phase calibrators can also be used to calibrate for the amplitude of the detected signal and the position of the radio source, however the flux density of a phase calibrator is often too variable and can change significantly over time. Therefore, a primary flux calibrator that has a known, bright and constant flux density is observed once throughout the observations to calibrate the flux. The primary flux calibrator for the Australia Telescope Compact Array (ATCA) is 1934–638 and this is observed for ~ 10 minutes each observing session.

If any spectral line observations are being conducted, an additional calibrator known as a bandpass calibrator is required. The bandpass needs to be a bright point source of known flux density and is used to calibrate the response of the spectral line bandpass as a function of frequency. The ATCA uses 1253–055 as the bandpass calibrator, which is stable, and therefore only needs to be observed once per observation.

In general, a phase calibrator is observed for 1–2 minutes every 20–25 minutes. A single 10–15 minute observation of the primary flux and bandpass calibrator is generally sufficient. However, calibration durations depend on both weather conditions and the specific scientific goals. In poor weather, the interval between phase calibrator

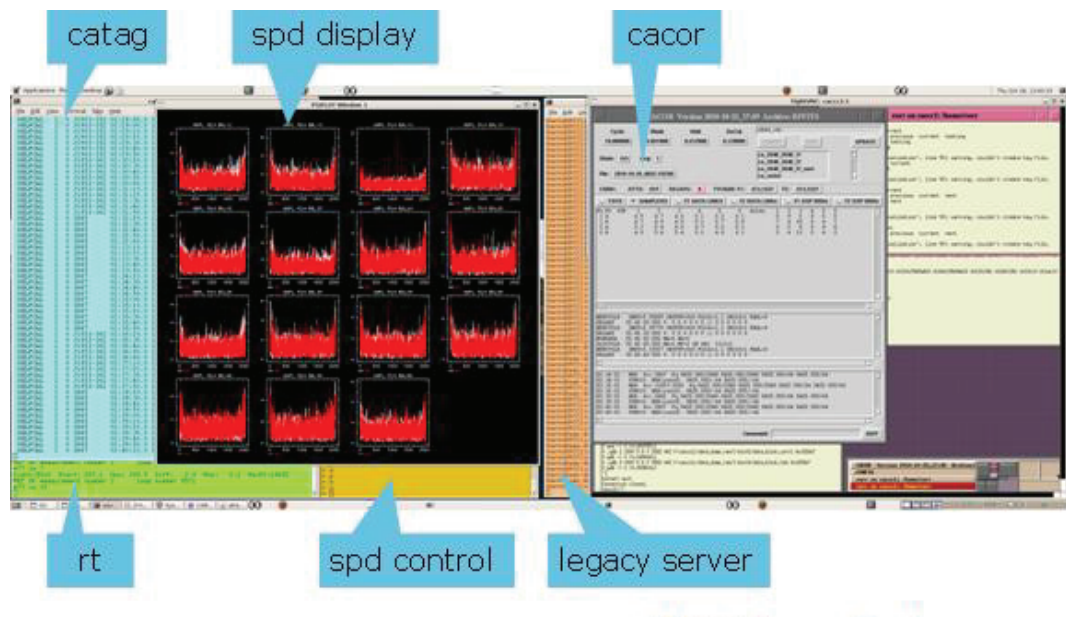
observations is reduced to more precisely track atmospheric variations. Additionally, if highly accurate flux or bandpass calibration is required, longer integration times may be necessary.

2.3 THE ATCA

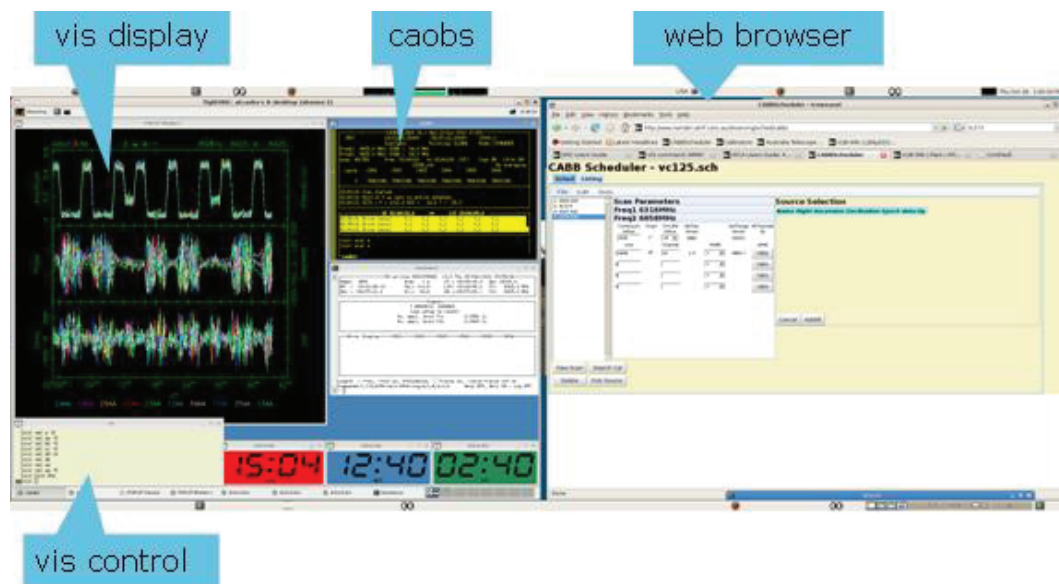
All the radio continuum data presented in this thesis were obtained using the Australia Telescope Compact Array, an Earth-rotation aperture synthesis radio interferometer. The ATCA is an array of six 22 m antennas located 237 m above sea level at latitude $-30^{\circ} 18' 46.385''$ south and longitude $149^{\circ} 33' 00.500''$ east. The array has a 3 km east-west track with a 214 m northern spur. Five of the antennas can be moved along these tracks, with the sixth antenna fixed 3 km to the west of the east-west track. The ATCA supports 17 standard configurations designed to maximise uv -coverage while minimizing redundancy during a typical 12-hour observing period. This allows the antennas to be positioned in various configurations with a maximum and minimum baseline of 6 km and 30 m, respectively.

2.3.1 OBSERVING WITH THE ATCA

The initial observational data presented in Chapter 3 of this thesis were collected by Titmarsh et al. (2014, 2016) and extracted from the Australia Telescope Online Archive (ATOA). The data presented in Chapters 4 and 5 were obtained through three observing sessions conducted by myself. The first set of observations was conducted remotely in March 2022. These high-resolution observations were designed to follow up on potential HCHII regions identified from an archival dataset (discussed in more detail in Chapter 3). The March 2022 data and the results are presented in Chapter 4. The second set of observations took place at the Science Operations Centre (SOC) in Marsfield, Sydney in July 2022, while the final session was conducted remotely in August 2023. The data from both the July 2022 and August 2023 sessions are covered in Chapter 5. This section provides a brief overview of the procedure followed during



CACCC1 vnc display



XBONES vnc display

FIGURE 2.7: Typical VNC display from the desktop at Narrabri, used for remote ATCA observations. The display includes multiple monitoring and control interfaces: the CAOBS window for executing observing commands, the CACOR interface for correlator control, and the VIS display for real-time data visualization. Additional panels include the SPD display for spectral data, the web browser for reference materials.

these observations, which can be summarized in four key steps:

- *Connect and Prepare:* Observations are controlled through a Virtual Network Connection (VNC), which requires connecting to two VNC sessions: **CACCC1** and **XBONES**. The **CACCC1** session facilitates communication with the correlator via **cacor**, while **XBONES** manages overall array control, primarily through **caobs**. **Caobs** is the primary interface between the observer and the telescope. It coordinates the functions of the antennas and the correlator. An example of this setup is shown in Fig. 2.7. Additionally, the observing portal is loaded to enable direct communication with the duty astronomer, ensuring real-time troubleshooting and coordination during the observing session.
- *Set up and Calibrate:* The array is typically pre-configured to the desired setup, with the Compact Array Broadband Backend (CABB; Wilson et al. 2011) correlator tuned to the appropriate observing frequency. Calibration begins by observing a strong continuum point source. Depending on the wavelength being observed, the correlator is adjusted, and delay offsets are calculated. This involves determining differences in signal arrival times between antennas to ensure accurate alignment across all baselines. A delay calibration scan is then run, where the correlator averages the visibilities over a narrow frequency band, specifically targeting instrumental delays. Once the delays are applied, the visibility amplitudes are scaled to the correct flux density by comparing the measured flux of the calibrator to its known value, ensuring the data remains consistent with the standard flux density scale.
- *Observation Planning and Execution:* Once the array is calibrated, science observations begin by collecting additional calibration data. These observations are conducted using the *snapshot method*, which involves performing a series of short observations at different hour angles to improve *uv* coverage across a large number of sources. The calibration process starts with a 10-minute observation of a bandpass calibrator, a bright source with high flux density and well-established properties such as position and size. This step is essential for

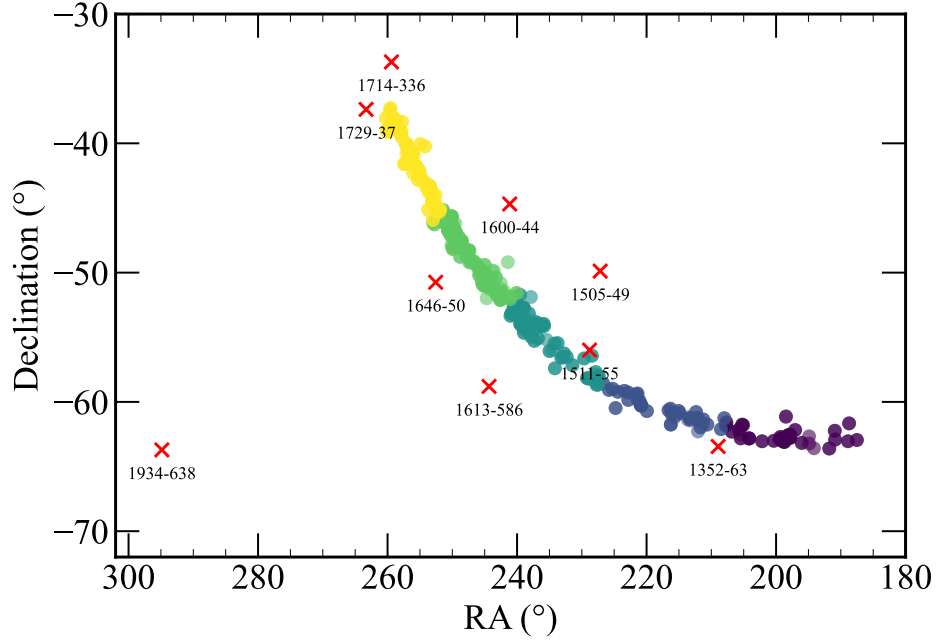


FIGURE 2.8: Sky distribution of observed sources in the SCOTCH survey. The coloured markers indicate sources grouped into 10-degree bins in Galactic longitude. Red crosses represent the phase calibrators associated with each 10-degree bin. The outlier, 1934-638, marks the position of the primary flux calibrator.

correcting instrumental phase variations and mitigating atmospheric effects. Additionally, it ensures accurate amplitude calibration, enabling precise flux density measurements of the target sources throughout the observing session. A schedule file, prepared before the observations, automates the sequence of scans, specifying frequencies, correlator settings, and durations. Each scan represents a continuous period where the telescope configuration remains fixed. The schedule alternates between blocks of science targets and phase calibrators, with phase calibrators observed at the start and end of each block to correct for atmospheric variations. Science targets are grouped into blocks, typically within 10 degrees of each other, to minimize telescope slewing time and optimize the observation process. Each target source is observed for 2 minutes at least 6 times throughout the observing period to maximize the uv sampling and ensure good coverage. Figure 2.8 shows the sky distribution of targets observed as part of SCOTCH, with sources grouped by colour in 10-degree Galactic longitude blocks. Each block is paired with a nearby bright phase calibrator, marked by red crosses. This approach is applied consistently across all three observational datasets used in this thesis.

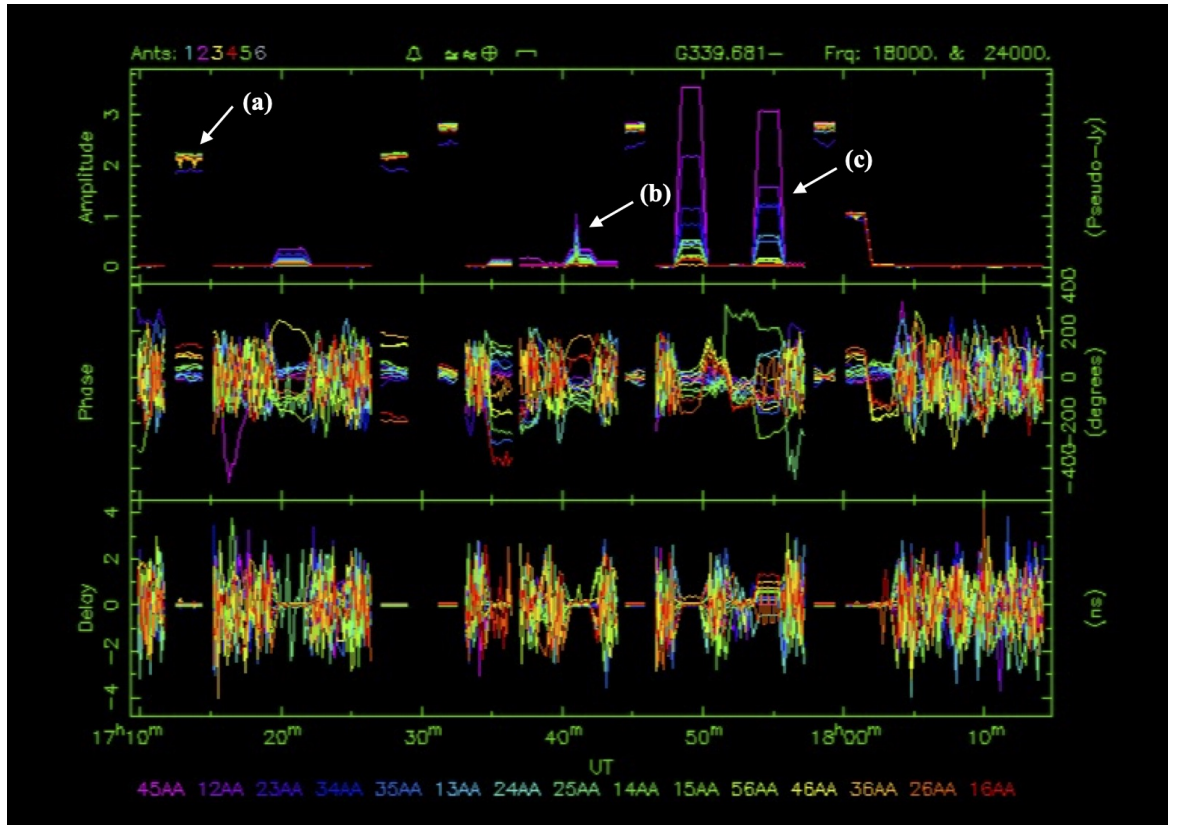


FIGURE 2.9: A figure showing the VIS panel of the ATCA, which provides a real-time overview of the amplitude, phase, and delay vs time during observations. The coloured lines represent the 15 different baselines used in the array configuration. Label (a) shows a phase calibrator with stable flux and phase, label (b) highlights interference from RFI, and label (c) represents a resolved source.

Monitoring the quality of observations is a critical part of the process, ensuring that data anomalies, instrumental issues, or external interference are properly identified. This is achieved using the **VIS** display, a panel in **XBONES** that provides a real-time visualization of the data quality during observations. In Figure 2.9, we present the **VIS** display used to monitor our observations, which consists of three key plots: amplitude vs. time (top), phase vs. time (middle), and delay vs. time (bottom). As the schedule file runs, we continuously track these plots for significant changes or anomalies. Label (a) marks the typical response of a phase calibrator. The stable phases and low delays confirm that the incoming radiation is coherent and unresolved, which is expected from phase calibrators. These sources are known point sources with stable flux densities, serving as reliable references for calibration. Label (b) highlights an example of a radio frequency interference (RFI) spike. When this type of interference is detected, we note which science sources and their associated calibrators are affected, so these data can be flagged and removed during the reduction process. Finally, label (c) shows the **VIS** display of a well-resolved science target. The coloured lines represent the signals from the 15 baselines, with each line corresponding to a different antenna pair. As seen in the amplitude vs. time plots, the amplitude decreases across the baselines, indicating that the structure of the source is being resolved on longer baselines. This decrease in amplitude further confirms the resolved nature of the source.

- *Monitor*: Once observations are underway, the array takes care of most operations autonomously. It monitors local wind conditions every 2.5 seconds and automatically stows if the average wind speed exceeds 40 km/h over a 10 second period. Similarly, if thunderstorms or lightning strikes are detected within a 9 km radius, the array stows for protection. At this stage, it is time to make a cup of tea and monitor the vis display for any RFI spikes or data anomalies while the system runs smoothly.

2.3.2 DATA REDUCTION

All of the data presented in this thesis were processed using the **MIRIAD** data reduction package (Sault et al., 1995a), following the standard ATCA procedures. The following section provides a brief overview of the data reduction steps used in our analysis, with Figure 2.10 outlining the calibration pipeline. Each step is explained in more detail in the following paragraphs.

2.3.2(a) CALIBRATION

Loading the Data

We begin by loading the raw data, which is provided in the ATNF-specific RPFITS format. Due to the 4GB limit of the ATCA correlator, ~ 6 RPFITS files are generated over a typical 12-hour observing period. To prepare the data for further analysis, we use the **ATL0D** task, which converts the RPFITS files into the **MIRIAD** *uv* format. This task also combines the multiple RPFITS files into a single *uv* dataset, which simplifies the process of splitting the data by frequency. Since our observations were conducted at both 18 and 24 GHz simultaneously, the combined dataset is then split by frequency using the **UVSPLIT** task. This task separates the data into individual datasets for each frequency band, allowing us to analyse each band independently.

Inspecting the Data

With the data now split into frequency-specific bands, the next step is to inspect the raw diagnostic plots and flag any bad data or RFI. There are a few key diagnostic plots that we use to help us identify any anomalies:

- *uv coverage*: A *uv* coverage map illustrates the tracks traced by the antennas in the *uv* plane as the Earth rotates, representing the spatial frequency coverage of the observations. The density and distribution of these tracks determine the telescope’s ability to reconstruct source structures and resolve spatial details. A well-sampled *uv* coverage improves image quality and reduces sidelobe effects. The top row of Figure 2.11 shows an example of a poorly sampled (left) *uv* plane versus a well-sampled (right) *uv* plane.

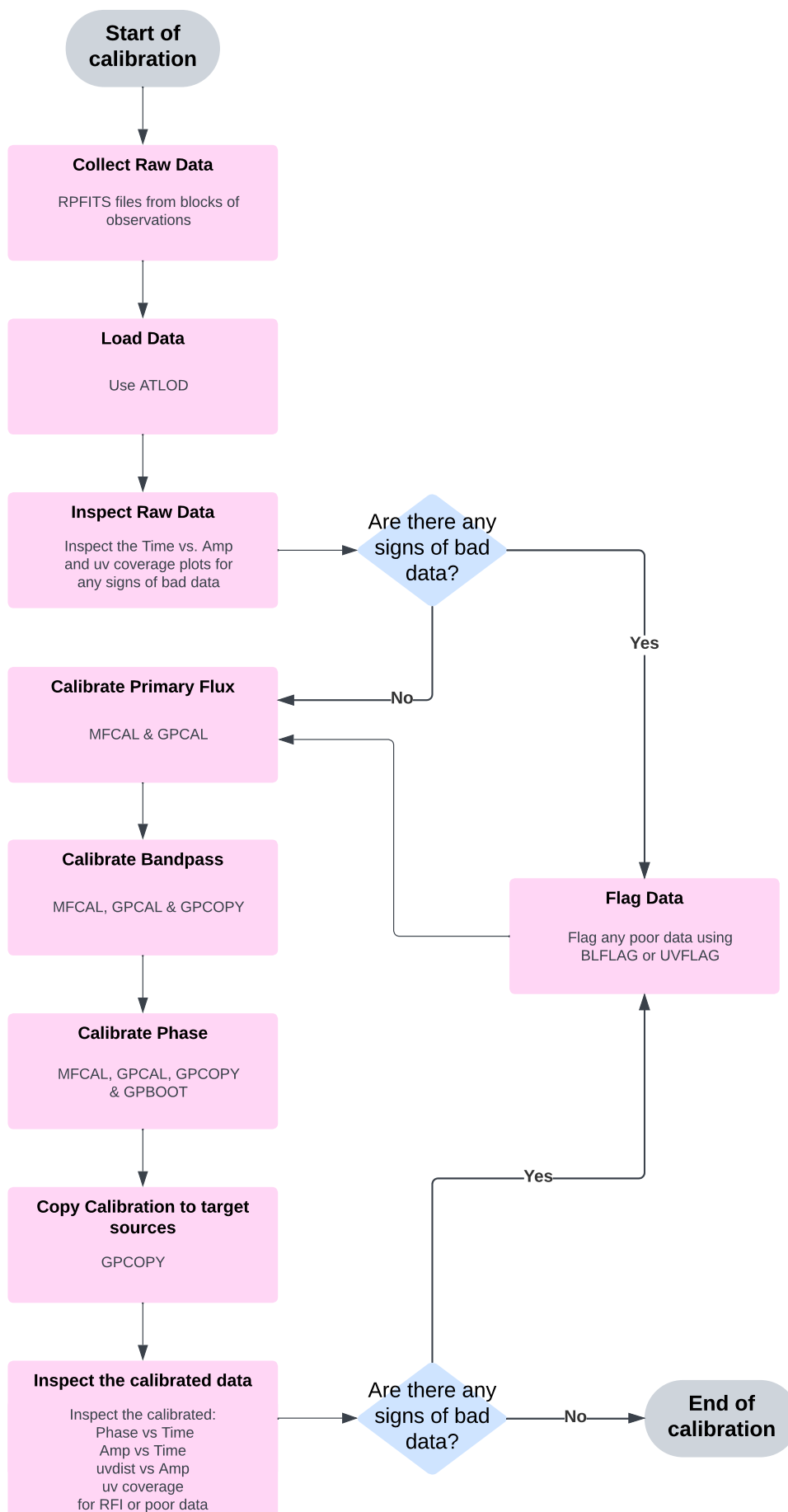


FIGURE 2.10: A detailed flowchart illustrating the calibration procedure for raw data. Pink boxes denote processing steps, while blue diamonds indicate decision points.

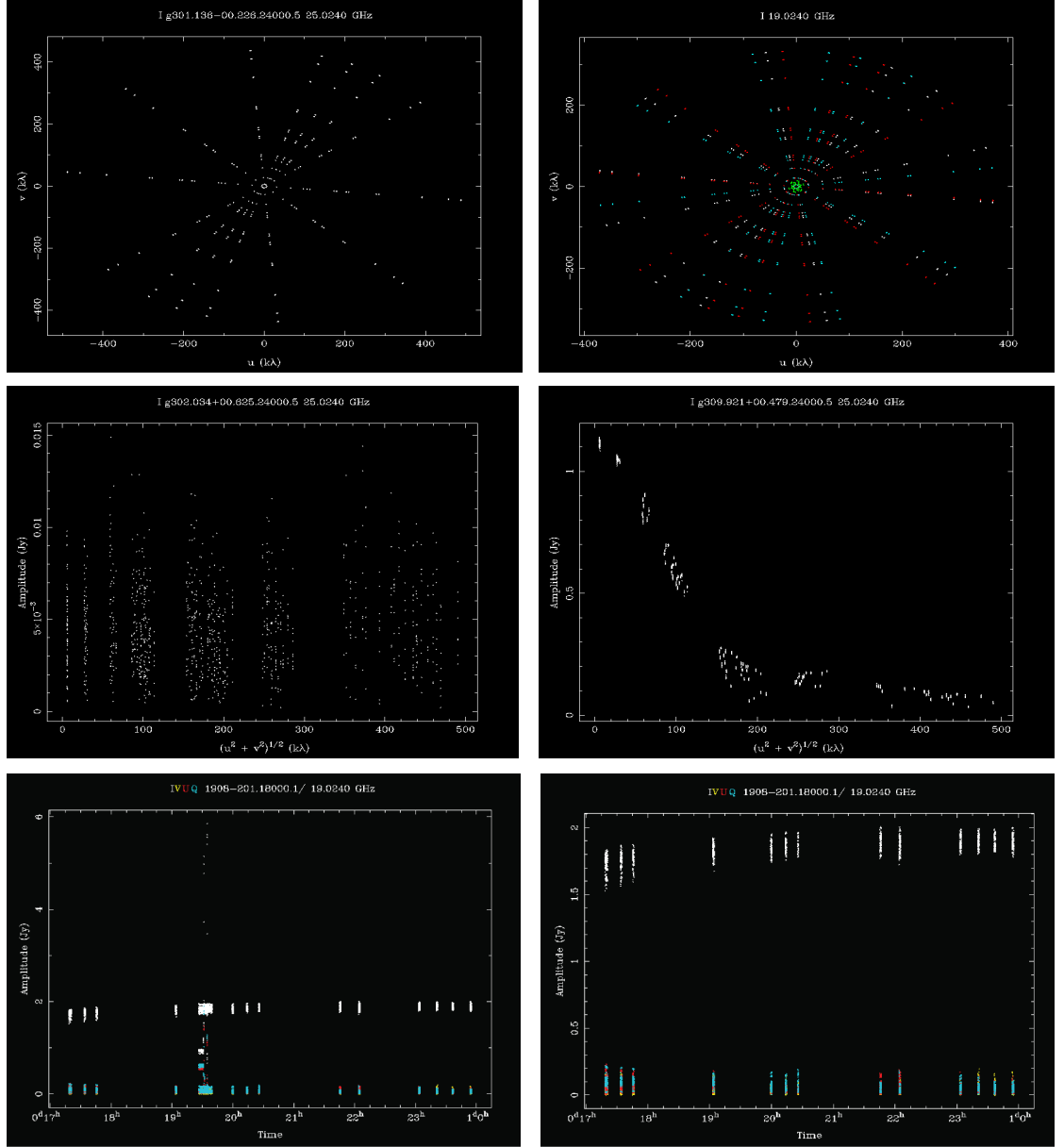


FIGURE 2.11: The top row presents uv -coverage maps, showing the spatial frequency sampling of the observations. The left panel illustrates a poorly sampled uv plane, while the right panel shows a well-sampled uv plane with denser coverage, where colours represent the addition of visibilities from multiple observations. The middle row displays amplitude versus uv distance plots, illustrating how flux density varies with baseline length. The left panel corresponds to an unresolved source, exhibiting nearly constant flux, while the right panel shows a resolved source with a characteristic Gaussian-like drop in flux density at longer baselines. The bottom row presents amplitude–time plots used to identify visibilities affected by RFI or other poor-quality data before imaging.

- *Amplitude vs. uv distance*: These plots display the flux density measured on each baseline as a function of uv distance, expressed in kilo-lambda ($k\lambda$). They provide insight into how the flux density varies with baseline length and are used to assess whether a source is resolved or unresolved. An unresolved source maintains a nearly constant flux density across all baselines, whereas a resolved source shows a characteristic Gaussian-like decline at longer baselines due to the spatial filtering of extended emission. The middle row of Figure 2.11 illustrates this difference, with an unresolved source shown on the left and a resolved source on the right.
- *Amplitude vs. Time*: This plot shows how the flux density varies over time during the observing session. It helps us identify if any visibilities have been affected by RFI. In radio interferometry, we use these maps to detect visibilities that may be contaminated by RFI or simply indicate bad data. The map reveals the amplitude of flux density obtained at each hour of observation. An example of an amplitude-time map is shown in the bottom row of Figure 2.11. In the right-hand panel, we show how RFI can affect the data, while the left-hand panel shows the data after the interference has been flagged out. This will be discussed in more detail in the following section.

RFI has a significant impact on astronomical observations. Man-made radio signals from sources such as mobile phones, wireless networks and garage door openers can overwhelm faint cosmic radio signals. While most forms of RFI can be partially removed during data processing, their presence can heavily compromise the efficiency and usability of the data.

Flagging

Once the diagnostic plots have been inspected, we proceed with flagging any bad data or RFI using essential MIRIAD tasks: **UVFLAG** and **BLFLAG**. These tools allow us to remove problematic data, ensuring the integrity of the observations.

UVFLAG is used to flag specific chunks of data, such as when an RFI spike is observed. If a spike appears on the visibility panel (see Fig. 2.9), we can identify the affected calibrator and note the time of the interference. During calibration, **UVFLAG**

is applied to exclude the contaminated visibilities within that time frame, preventing them from impacting the final results.

BLFLAG (short for baseline flag) is used to flag data on specific baselines. If deviations in flux density are detected while inspecting the data, **BLFLAG** allows us to manually remove these anomalies, ensuring that bad data does not compromise the overall dataset quality. By carefully addressing both time-based and baseline-specific issues, we can effectively mitigate the effects of RFI and other anomalies, resulting in cleaner and more reliable data for subsequent calibration and analysis.

The bottom left panel of Fig. 2.11 shows an amplitude versus time plot for a phase calibrator affected by RFI, while the right panel displays the same calibrator after the RFI-contaminated visibilities have been flagged and removed. Once all calibrators have been properly flagged and any bad data has been eliminated, we are ready to proceed with calibration.

Calibration

The calibration process begins with the primary flux calibrator, which is essential for setting the absolute flux density scale. The task **MFCAL** is used to determine the antenna gains, bandpasses, and delays, assuming the primary calibrator is a point source. For our observations, we used 1934-638 as the primary flux calibrator, which is the recommended standard for the ATCA at 15 mm. This source is particularly well-suited for calibration due to its known and stable flux density across a broad frequency range and is bright enough to provide a strong signal for accurate calibration. **MFCAL** is applied first to this source, and then **GPCAL**, which refines the antenna gains and corrects for polarisation leakages. This ensures that any instrumental or atmospheric effects are removed, and the absolute flux scale is set accurately.

Once the primary flux calibrator is fully calibrated, we move on to the bandpass calibrator (1253-055) and phase calibrators. These are calibrated in the same manner but with an added step to maintain consistency across all calibrators. To achieve this, we apply an amplitude bootstrap, where the calibration tables derived from the primary flux calibrator are transferred to the bandpass and phase calibrators. This ensures that the amplitude scales between these calibrators are consistent and minimises any

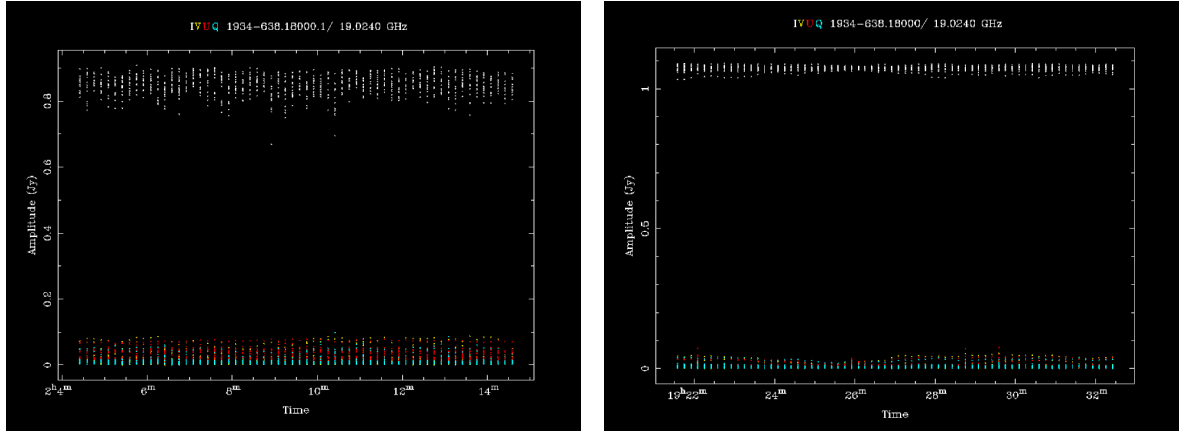


FIGURE 2.12: Amplitude–time plots of the primary flux calibrator before (left) and after (right) calibration.

inconsistencies that could affect the flux scaling of the target sources.

The next step is to copy the calibration tables to the target sources. This must be done carefully, as the phase calibrators are observed between specific target sources to account for atmospheric variations during the observation session. Each phase calibrator is applied only to its corresponding group of target sources.

The calibration process for our observations was automated using two shell scripts within MIRIAD, one for calibration and one for imaging. This approach was chosen to ensure consistency and minimise the potential for human error. At each stage, visibility plots were generated to verify the success of the calibration. Key diagnostic plots, such as amplitude vs. time, were closely examined to confirm that the calibration had been applied correctly. Figure 2.12 shows a comparison between a properly calibrated primary flux calibrator and one that has not been calibrated. We specifically check for steady and consistent amplitude across all calibrators. A stable amplitude indicates that the calibration was successful and that the data is ready for imaging.

2.3.2(b) IMAGING

To reconstruct the true image of our data, we must deconvolve it to remove the influence of the dirty beam. In MIRIAD, this is achieved through the following steps:

Invert:

The `invert` task is used to convert the observed visibilities from the uv plane into an

initial sky image by applying a Fourier transform. This process produces a preliminary “dirty” image, $I_D(l, m)$ (Eq. 2.49), which represents the observed intensity distribution. Incomplete sampling of the uv plane introduces side lobes and artefacts in the dirty image, adding uncertainty to the representation. Alongside the dirty image, `invert` also generates a dirty beam, $B(l, m)$ (Eq. 2.52), which characterises the point spread function of the array. To ensure optimal imaging, a robustness weighting (`robust=0.5`) was applied, striking a balance between sensitivity and resolution. A flux density cut-off of 4×10^{-4} Jy excluded weak noise, ensuring that only significant emission features were retained in the resulting image. The specific image size and pixel scale for each set of observations varied and will be discussed later in the context of high and low-resolution imaging.

Clean:

Once the dirty image has been produced, the next step in the imaging process is to remove the side lobes and artefacts introduced by the Fourier transform. This is achieved using the `CLEAN` task, which deconvolves the dirty image. The `CLEAN` algorithm works by iteratively identifying and subtracting point sources from the dirty image, creating “clean” components that represent the true emission. These components are then convolved with a Gaussian restoring beam, which is the same beam used in the dirty image, to produce a cleaner and more accurate final image. For our analysis, the `CLEAN` task was executed with a maximum of 1000 iterations to ensure sufficient convergence. The process continued until the residuals were below a specified cut-off value, which is set to eliminate weak noise. The algorithm was also configured to stop cleaning when negative values in the image reached a threshold preventing over-subtraction of emission and ensuring that only the significant features were retained in the final map.

Restor:

The `RESTOR` task is applied to refine the image by restoring it to its true intensity distribution. After deconvolution with `CLEAN`, residual artefacts may remain, and the image might not fully capture the observed flux. The `RESTOR` task adds the clean components, convolved with the Gaussian restoring beam, back to the residuals, ensuring

accurate flux recovery and proper representation of point sources.

Linmos:

The final step involves correcting for the primary beam effects using the LINMOS task. The primary beam correction is necessary to account for the variation in sensitivity across the field of view, particularly if the source is not located at the centre of the image. The LINMOS task normalizes the restored image by dividing it by a model of the primary beam and re-scaling it to ensure consistent sensitivity across the entire image. This step corrects for the flux density variation, ensuring that sources located away from the centre of the field are accurately represented.

2.3.2(c) IMAGING RESOLUTIONS

Low-Resolution:

For low-resolution imaging, we took 5-6 snapshots per target each day, depending on its sky position, with approximately 10 minutes of integration time per snapshot. This setup enhanced sensitivity to large-scale emission, making it ideal for capturing extended regions around embedded objects. The image size was set to 120 x 120 pixels, with a cell size of 1 arcsecond, resulting in a final image size of 2 arcminutes (120 arcseconds) on each side. We used the H214 configuration, which provided an angular resolution of 20 arcseconds. The maximum and minimum baseline lengths were 247 m and 83 m, respectively. Additionally, the sixth antenna was not used due to its exclusion from the observation setup, leading to a gap in uv coverage. Figure 2.13 shows the uv coverage, synthesized beam, and both dirty and restored images. Further imaging details are provided in Chapter 3.

High-Resolution Imaging:

High-resolution imaging was achieved by combining data collected over several days, significantly improving uv coverage and enhancing sensitivity to small angular scales. Observations were conducted six times daily over three days, resulting in a total of 30 minutes of integration time per target. The image size was set to 256 x 256 pixels, with a cell size of 0.2 arcseconds, resulting in an image size of approximately 50 arcseconds

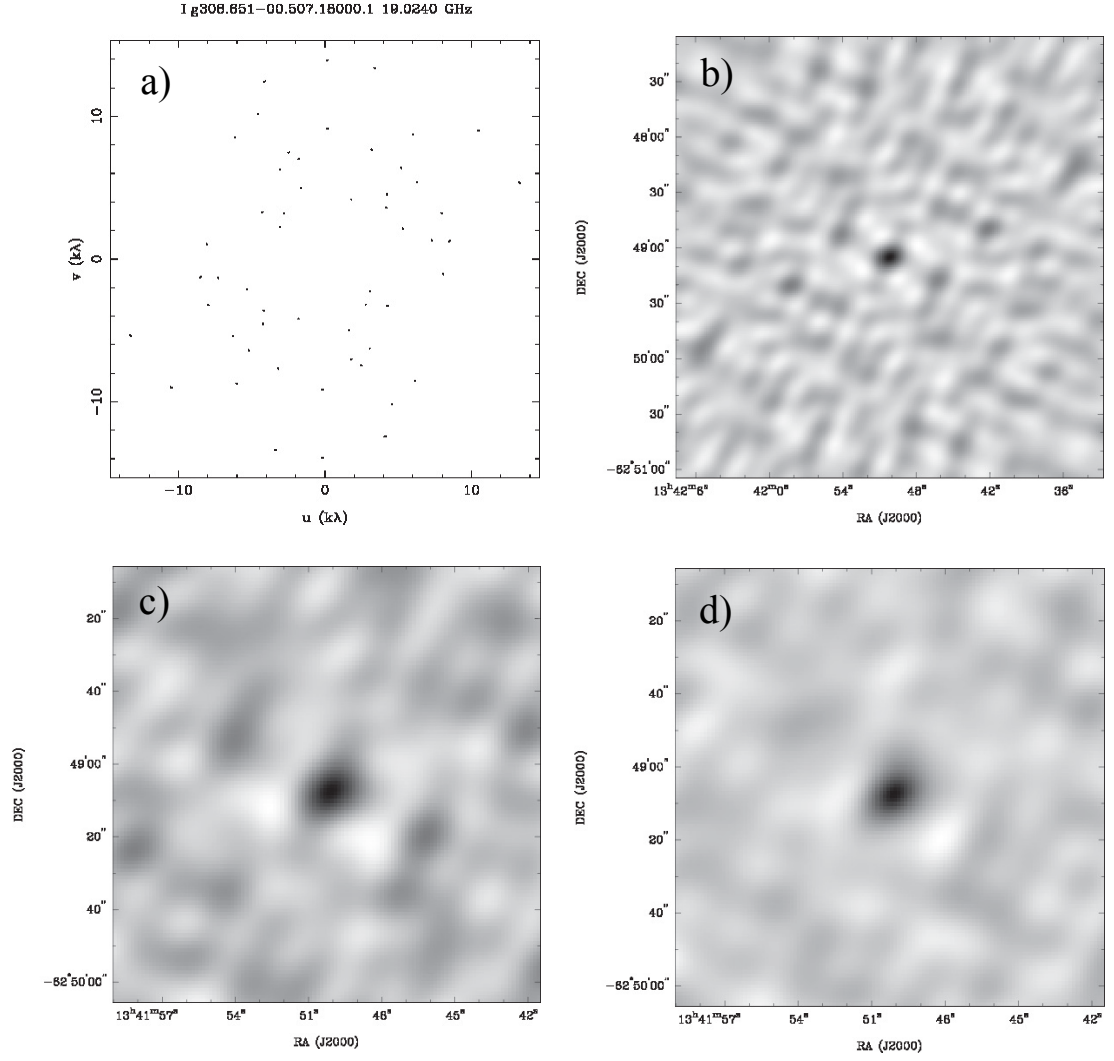


FIGURE 2.13: Low-resolution imaging of radio source G308.651–00.507, showing uv coverage (a), synthesized beam (b), and dirty (c) and restored image (d). Limited uv coverage leads to notable contamination.

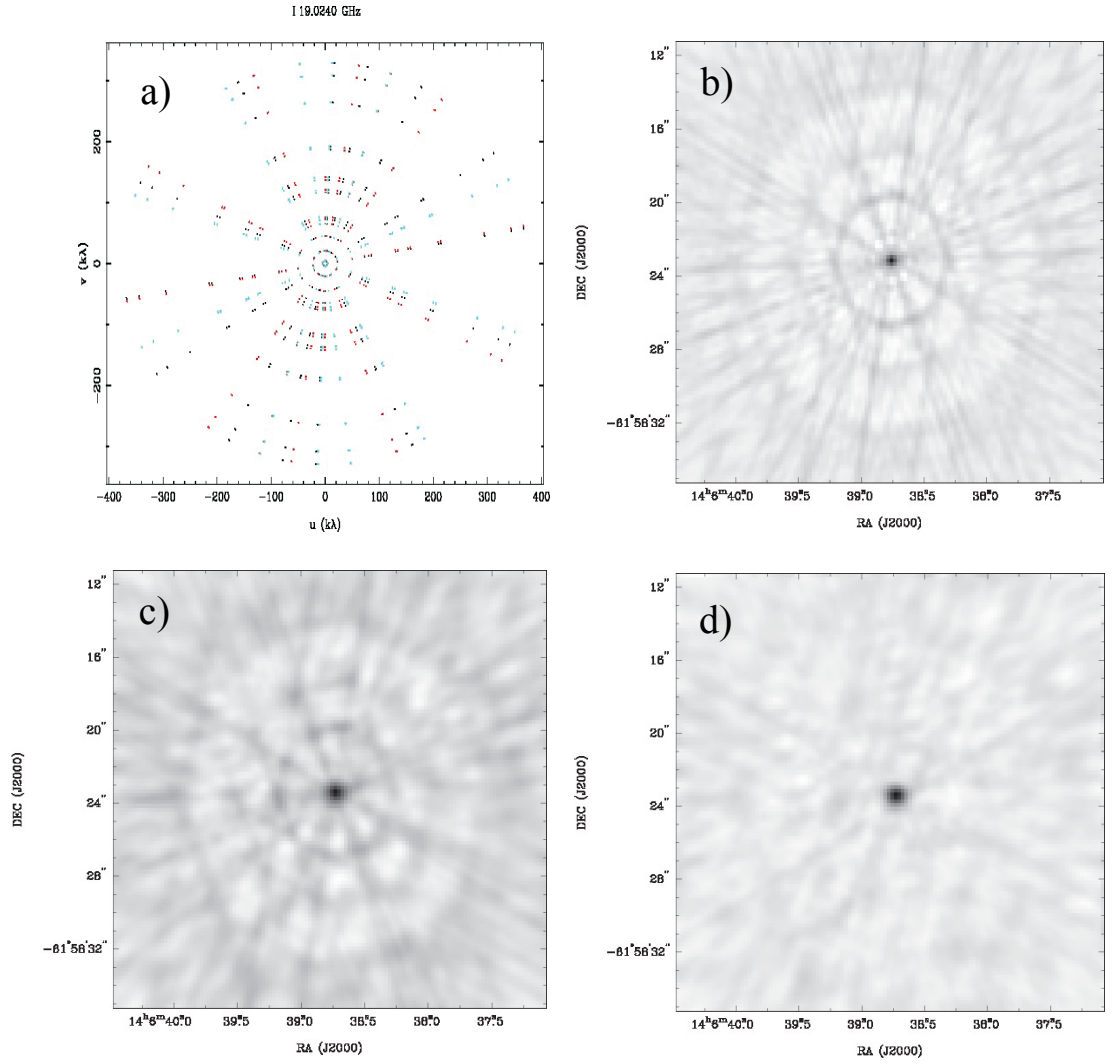


FIGURE 2.14: High-resolution imaging of radio source G311.643–00.380, showing the same maps as Fig. 2.13. The uv coverage plot illustrates the observed visibilities conducted over three separate days, represented by the red, blue, and black lines.

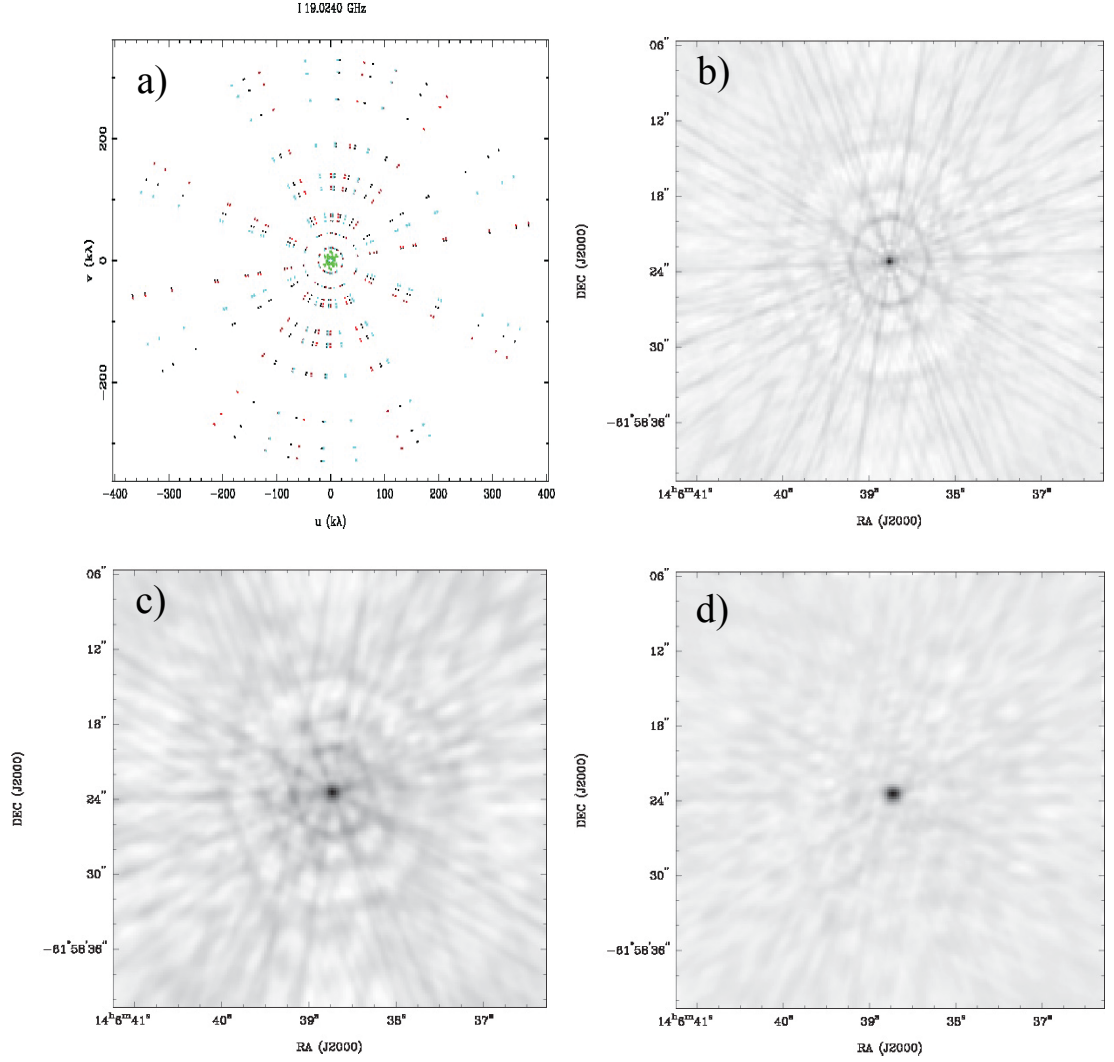


FIGURE 2.15: Combined-resolution imaging of radio source G311.643–00.380, illustrating the same maps as Fig. 2.13. The uv coverage plot includes high-resolution data represented by red, blue, and black lines, while green indicates low-resolution coverage, enhancing sensitivity to both fine and large-scale structures.

and a finer resolution of about 0.5 arcseconds. The maximum and minimum baseline lengths were 5939 m and 337 m, respectively. Unlike the low-resolution setup, the sixth antenna was included in the observation, and the linear configuration was used instead of the hybrid configuration. Figure 2.14 illustrates the setup, showing uv coverage, and both dirty and restored images. Chapter 4 provides further details on the high-resolution data.

Combined-Resolution Imaging:

To maximise image quality, we combined low- and high-resolution visibilities, resulting

in optimal uv coverage. This extended coverage improves sensitivity across a wide range of angular scales, allowing us to capture both large-scale and fine structural details with high precision. The image size was set to 256 x 256 pixels, with a cell size of 0.2 arcseconds, as in the high-resolution setup. By combining the datasets, we achieved maximum uv coverage, which enhanced the sensitivity to both large and small angular scales. Further details on this combined imaging approach are discussed in Chapter 5.

CHAPTER 3

SCOTCH I – THE PILOT

Understanding the earliest stages of high-mass star formation remains a central challenge in astrophysics, with the youngest HII regions often deeply embedded and difficult to detect. Methanol masers are thought to trace these early phases, but the extent to which they pinpoint the most compact and recently formed HII regions is still uncertain.

This chapter presents a pilot study using archival high-frequency radio continuum data from a water maser survey towards Class II methanol masers (Titmarsh et al., 2014). The data and analysis presented in this chapter are based on work previously published by the author Patel et al. (2023), but have been expanded here to provide fuller methodological detail and to place the pilot study within the wider SCOTCH thesis framework. Overall, this pilot study demonstrates that combining high-frequency radio continuum observations with methanol maser selection provides a practical and effective way to identify young compact HII regions.

As the first of the SCOTCH science chapters, this work establishes the observational and analytical framework adopted throughout the thesis. A consistent method is developed to identify and characterise compact high-frequency radio sources associated

with methanol masers, providing a robust basis for selecting candidate HC HII regions for higher-resolution follow-up in subsequent chapters.

3.1 INTRODUCTION

Class II 6.7 GHz methanol masers are widely recognised as reliable tracers of embedded high-mass star formation in its early evolutionary stages (Breen et al., 2013). These masers are radiatively pumped by the strong mid-infrared radiation produced by massive young stellar objects (MYSOs; Cragg et al. 1992), and therefore require the presence of a deeply embedded and luminous protostar. Observational studies of molecular outflows associated with methanol masers suggest that the maser phase begins after the earliest outflow-dominated stage of star formation, once accretion onto the protostar has generated sufficient luminosity to warm the surrounding envelope (de Villiers et al., 2015; Urquhart et al., 2022; Billington et al., 2019b). Methanol masers are thus expected to trace a stage shortly after the formation of a high-mass protostar. The key question addressed here is whether the subset of methanol maser sites with high-frequency radio continuum emission represents the earliest detectable stage of compact ionisation.

Despite this close association with young massive stars, only a fraction of methanol masers are found to be associated with detectable centimetre radio continuum emission. For example, a targeted 5 GHz radio continuum study by Hu et al. (2016) found that only approximately 30 per cent of methanol masers are associated with compact radio emission. More recently, Nguyen et al. (2022) reported a lower association rate of 12 per cent using data from the unbiased Global View of Star Formation in the Milky Way (GLOSTAR; Brunthaler et al. (2021)) survey. These relatively low association rates suggest that many methanol maser sources have either not yet developed detectable HII regions, or host ionised nebulae that remain weak or optically thick at lower radio frequencies.

Further evidence that methanol masers trace deeply embedded massive proto-

stars comes from infrared and submillimetre observations. Jones et al. (2020) characterised MYSOs hosting 6.7 GHz methanol masers identified by the MMB survey and found that almost 73 per cent of Class II methanol masers are associated with compact emission in four Hi-GAL far-infrared and submillimetre bands (70, 160, 250 and 350 μm ; Molinari et al. 2010b). Emission at these wavelengths arises from warm dust that reprocesses the ultraviolet radiation from the embedded protostar. The resulting infrared radiation field is responsible for pumping the Class II methanol masers. Methanol masers therefore provide an effective way to identify young high-mass protostars prior to the formation of a UC HII region.

Taken together, these studies suggest that the methanol maser phase begins shortly after the formation of a high-mass protostar and can persist into the earliest stages of ionisation, including the HC HII region phase, before eventually disappearing as the HII region expands and evolves into an UC HII and subsequently into a compact HII region (e.g. Walsh et al., 1998). Methanol masers are likely to be associated with the earliest stages of high-mass protostellar objects ($>3 M_{\odot}$; Minier et al. 2003) and provide a natural starting point for searching for very young ionised regions such as HC HII regions.

Building on this evidence, the present analysis uses archival ATCA high-frequency continuum observations targeted towards methanol masers identified by the Methanol Multibeam (MMB; Green et al. (2009)) survey. These data therefore provide a direct test of whether methanol maser sites preferentially host compact and potentially optically thick, HII regions.

3.2 OBSERVATIONS AND DATA REDUCTION

3.2.1 ARCHIVAL DATA

This chapter makes use of archival observations obtained with the Australia Telescope Compact Array (ATCA) between November 2010 and May 2016. The dataset covers 323 6.7 GHz methanol maser sources spanning Galactic longitudes 310° to 20° .

The original observing programme targeted water maser and ammonia emission, with spectral windows centred on the H₂O maser and the ammonia (1,1) and (2,2) transitions. The water maser results have been published by Titmarsh et al. (2014, 2016), while the ammonia and continuum components of the dataset remain largely unexplored. In this chapter, the focus is placed on the continuum emission, making use of previously unexploited continuum data towards 128 fields covering 141 MMB methanol maser sources. The data were retrieved from the Australia Telescope Online Archive¹.

3.2.2 SUMMARY OF OBSERVATIONS AND IMAGING

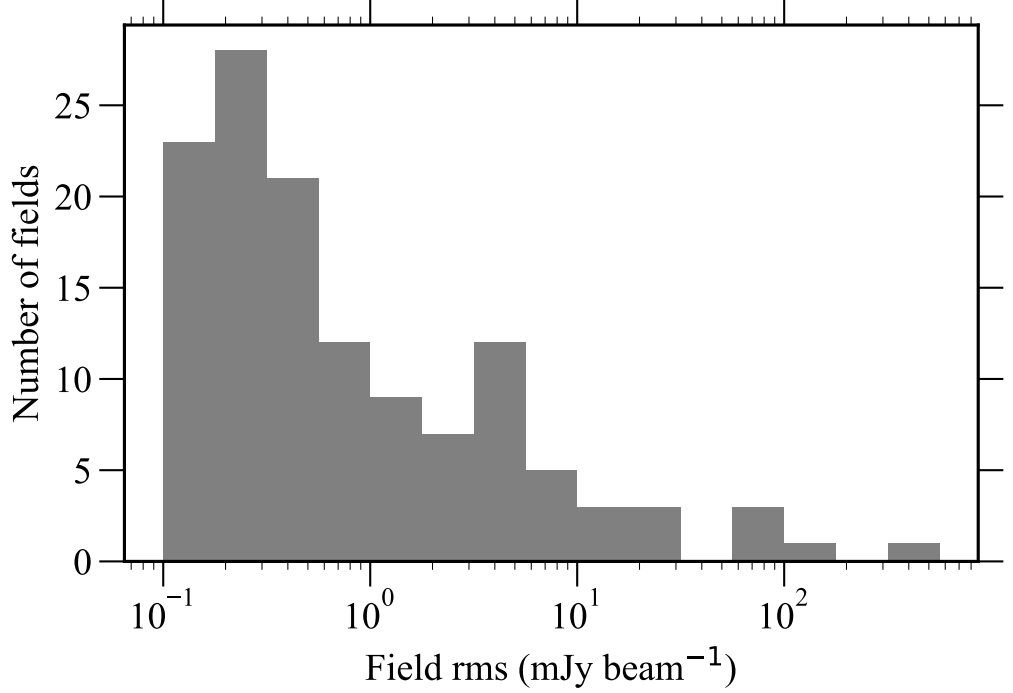
Observations were carried out using several compact ATCA configurations, utilising five of the six available antennas. The sixth antenna was excluded to avoid introducing a large gap in the *uv*-coverage, thereby ensuring more uniform spatial sampling.

The Compact Array Broadband Backend (CABB; Wilson et al. 2011) enabled simultaneous observations of broad-band continuum emission and high spectral-resolution line data. For this survey, two 2 GHz continuum bands were used, each divided into 32 channels of 64 MHz, centred at 22.235 and 23.708 GHz. These frequency ranges encompass the 22 GHz water maser and the ammonia (1,1) and (2,2) transitions, providing effective continuum coverage from 21.223 to 24.708 GHz.

To maximise observing efficiency, target sources were grouped according to their sky positions and observed in cycles, with nearby phase calibrators observed between target scans. Each methanol maser position was sampled multiple times over a six-hour period, resulting in at least four cuts in *uv*-coverage and a total on-source integration time of approximately six minutes per field. In cases where fields overlapped or were observed across multiple sessions, the corresponding datasets were combined to improve both sensitivity and spatial frequency coverage.

The data reduction and imaging procedures followed the standard methodology described in Section 2.3.2. For this dataset, channels containing the ammonia (1,1) and (2,2) transitions and the water maser line were excluded to isolate the continuum emis-

¹<https://atoa.atnf.csiro.au>



The rms distribution is strongly skewed, with a small number of fields extending to substantially higher noise values than the majority of the sample. To assess the scale of this effect, high-noise fields were identified using a threshold of five times the median rms value of the observed fields. The median rms of the 128 fields is $0.39 \text{ mJy beam}^{-1}$, giving a high-noise threshold of $1.95 \text{ mJy beam}^{-1}$. Using this definition, 31 fields are classified as higher-noise fields, corresponding to 24 per cent of the observed sample.

Inspection of these fields indicates that the elevated rms values are mainly associated with either bright compact emission, which limits the dynamic range of the snapshot observations, or extended emission and image undulations caused by incomplete spatial sampling. These effects are expected for interferometric observations of complex star-forming regions and do not necessarily indicate uniformly poor image quality across the whole map. Of the 31 higher-noise fields, 27 contain radio detections, and 14 of these detections are coincident with the targeted MMB methanol maser position. The remaining higher-noise fields either contain radio emission not associated with the methanol maser or are classified as non-detections.

The use of a local 3σ threshold means that the effective flux-density limit varies between fields, so faint compact sources may be harder to identify in the noisiest maps. The catalogue is therefore not treated as a complete flux-limited sample. Instead, the analysis focuses on robust detections and on the physical properties of the compact HII region candidates. The possible effect of the higher-noise fields on the final compact HII region sample is assessed explicitly in Section 3.3.2(b). These reduced maps form the basis for the source extraction and catalogue described in the following section.

3.2.3 SOURCE EXTRACTION AND FINAL CATALOGUE

With the reduced maps characterised, the next step is to identify radio sources and construct the final catalogue. Radio sources were identified relative to the local rms noise level measured for each field (Table 3.1). A nominal detection threshold of 3σ was used, such that only emission exceeding three times the local noise level was considered a potential source.

Source identification was carried out through visual inspection of each map.

TABLE 3.1: Summary of observational field parameters. Field names and pointing centres are based on the MMB source positions.

Field name	RA (J2000) (h:m:s)	Dec. (J2000) (d:m:s)	Field rms (mJy)	Major (arcsec)	Beam size Minor (arcsec)	Position angle (°)
G002.143+00.009	17:50:36.0	−27:05:47	0.49	11	6.7	72
G002.521−00.220	17:52:50.0	−27:05:26	0.31	11	6.7	72
G002.536+00.198	17:50:46.5	−26:39:50	0.31	11	6.7	71
G002.591−00.029	17:51:42.5	−26:44:33	0.35	11	6.7	71
G002.615+00.134	17:51:12.2	−26:37:40	21	12	6.7	71
G002.703+00.040	17:51:46.5	−26:36:23	0.33	12	6.6	71
G003.253+00.018	17:53:06.3	−26:08:29	0.78	11	6.6	72
G003.312−00.399	17:54:50.7	−26:18:23	0.39	11	6.6	72
G003.442−00.348	17:54:55.7	−26:09:50	9.3	11	6.6	72
G003.502−00.200	17:53:38.5	−26:55:53	0.39	11	6.6	72

Note: only a small portion of the data is provided here; the full table is available in Table 7.1 of the appendix.

Pixels above the 3σ threshold were used as an initial guide to locate regions of interest, after which each field was examined manually to determine whether the emission represented a genuine source. This approach was necessary due to the limited resolution of the data, which made automated detection methods less reliable.

In practice, genuine sources appear as localised, coherent regions of emission with a well-defined peak and a consistent structure across pixels. In contrast, imaging artefacts such as sidelobes typically appear as irregular or extended patterns that do not resemble real astrophysical emission. Distinguishing between these cases required careful inspection of each field, particularly in regions affected by higher noise levels or incomplete *uv*-coverage.

Figure 3.2 shows representative examples of the different types of emission encountered in the dataset: non-detections, compact sources, extended emission, multi-peaked emission, multiple resolved sources, and imaging artefacts. Examples of fields containing multiple radio sources are also included, illustrating both widely separated detections and cases where sources are too closely spaced to be reliably distinguished.

In total, 68 high-frequency radio sources were identified across the 128 observed fields. Unique source names were assigned based on their Galactic coordinates. The distribution of peak flux densities is shown in Figure 3.3, illustrating the distribution of detected source brightnesses across the sample, with most sources found at relatively

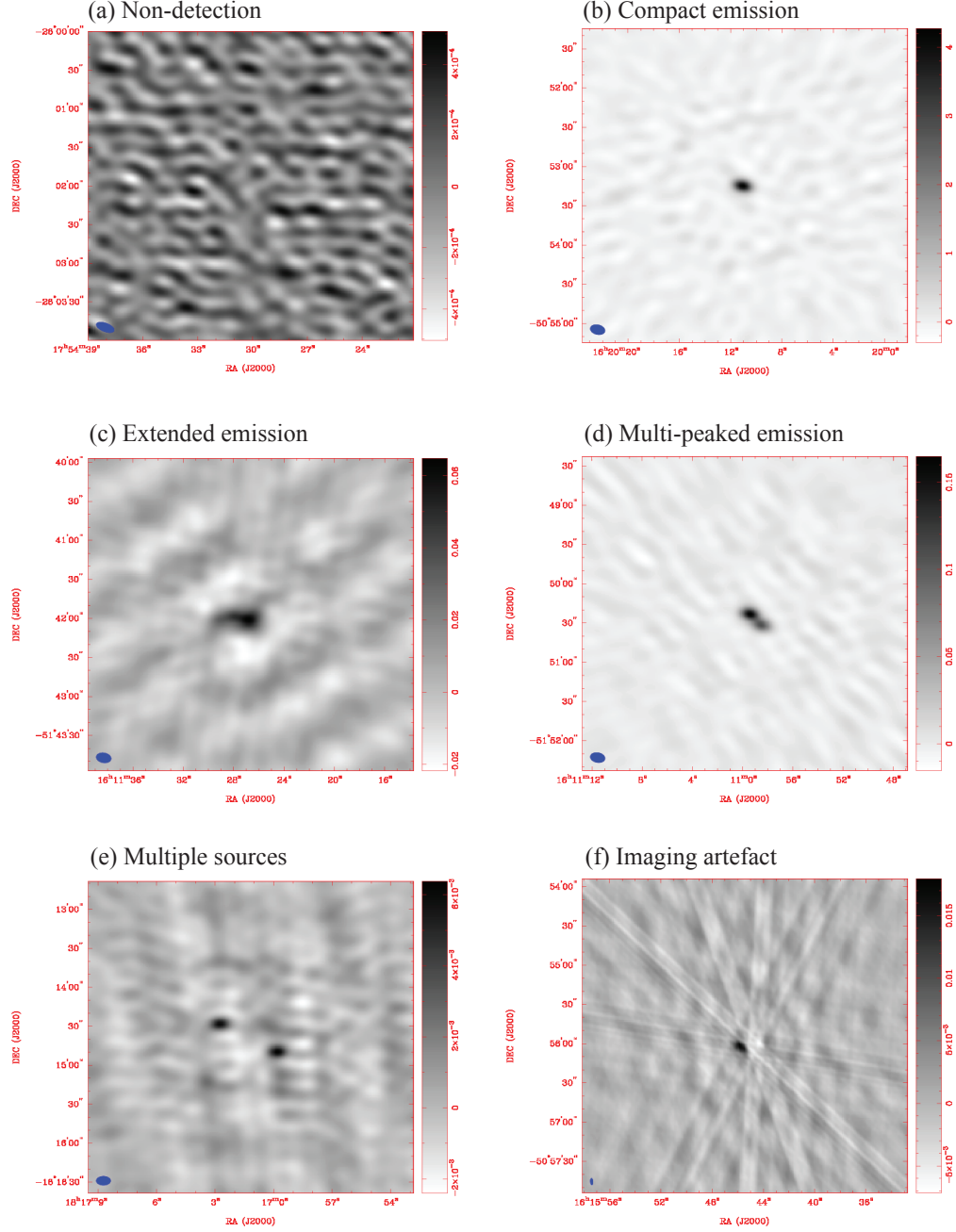


FIGURE 3.2: Representative examples of emission types identified in the dataset: (a) non-detection, (b) compact source, (c) extended emission, (d) multi-peaked emission that cannot be reliably separated into individual components, (e) multiple resolved sources within a single field, and (f) imaging artefact.

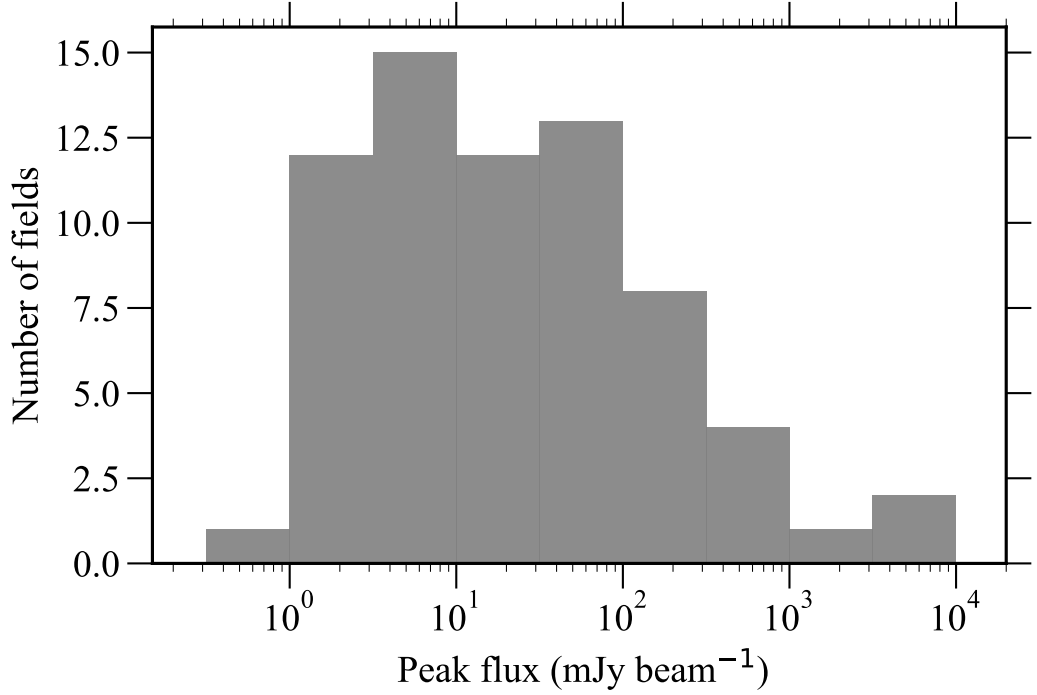


FIGURE 3.3: Histogram of the peak flux density of the detected radio sources. The histogram uses a bin size of 0.5 dex.

low flux densities.

Eight fields contain multiple radio sources, suggesting a degree of clustering. In three of these fields, the sources are too closely spaced to be reliably separated. In such cases, the emission was classified as multi-peaked and treated as a single source, with a single Gaussian component fitted to characterise the combined emission.

Five sources exhibit imaging artefacts caused by poor *uv*-coverage, typically appearing as large-scale undulations or false structures across the maps. These artefacts can mimic extended emission but lack the compact, coherent morphology expected for genuine sources. These sources are retained in the catalogue but are flagged to indicate that their derived parameters are less reliable, with representative examples shown in panel f of Figure 3.2.

Source parameters were derived using the MIRIAD task IMFIT, which fits two-dimensional Gaussian components to the emission. For each source, a polygon was manually defined around the region of interest, based on the visual identification of emission in the maps. This step provides the fitting algorithm with a constrained region in which to operate, effectively guiding it to the relevant emission and excluding

TABLE 3.2: Extracted source parameters from the detected radio sources. Column 1 gives the radio source name, derived from the Galactic coordinates of the fitted position. Columns 2 and 3 give the Right Ascension and Declination. Columns 4–7 give the peak flux density, peak-flux uncertainty, integrated flux density, and integrated-flux uncertainty at 23.7 GHz. Columns 8–10 give the fitted major axis, minor axis, and position angle.

Radio name	RA (J2000) (h:m:s)	Dec. (J2000) (d:m:s)	f_{peak} 23.7 GHz (mJy beam ⁻¹)	Δf_{peak} 23.7 GHz (mJy beam ⁻¹)	f_{int} 23.7 GHz (mJy)	Δf_{int} 23.7 GHz (mJy)	Major (arcsec)	Minor (arcsec)	Position angle (°)
G002.143+0.009	17:50:36.0	-27:05:47	6.6	0.29	8.4	0.52	15	7.8	63
G002.614+0.134	17:51:12.2	-26:37:40	170	7.8	230	15	16	8.2	69
G003.307-0.403	17:54:50.5	-26:18:15	2.9	0.3	3.7	0.55	15	8	65
G003.438-0.349	17:54:55.7	-26:09:47	94	2.8	100	4.4	14	6.9	67
G003.910+0.001	17:54:38.8	-25:34:44	93	3.1	100	4.9	15	6.7	66
G004.680+0.277	17:55:18.8	-24:46:29	9.8	0.31	10	0.47	14	6.8	67
G005.629-0.291	17:59:33.8	-24:14:20	2.9	0.16	8	0.64	19	13	77
G005.885-0.392	18:00:30.4	-24:04:01	7900	230	8400	350	14	7.1	71
G010.629-0.338	18:10:19.1	-19:54:10	36	2.4	46	4.4	11	7.9	-90
G011.904-0.141	18:12:11.2	-18:41:29	77	2	47	4.1	14	7.3	-89
G011.937-0.616	18:14:01.1	-18:53:23	660	34	930	68	11	8.1	72
G012.112-0.127	18:12:33.4	-18:30:06	0.68	0.056	0.86	0.11	13	7	-76

Note: only a small portion of the data is provided here; the full table is presented in Table 7.2 of the appendix.

surrounding noise or unrelated structures.

This constraint is particularly important when working with data of limited resolution and variable noise properties. Without the use of a polygon, **IMFIT** tends to prioritise the brightest pixel in the map and fit a Gaussian centred on that peak, often assuming it represents the full extent of the source. In fields containing multiple sources or extended emission, this can produce incorrect fits. Restricting the fitting region allows the algorithm to better characterise the intended source and produce more reliable measurements.

Because the detection threshold is defined relative to the local rms noise in each map, the effective flux-density limit varies between fields. The catalogue is therefore not strictly flux-limited, and faint compact sources are more difficult to detect in noisier images. For this reason, the detected sample is treated as a candidate catalogue rather than a complete census. The main conclusions are based on the properties of robust detections and on follow-up selection from those detections, rather than on deriving an unbiased luminosity function or absolute occurrence rate.

In two cases (G331.710+0.604 and G332.290-0.091), the emission could not be reliably fitted using **IMFIT** due to strong artefacts and complex morphology. For these sources, **SExtractor** was used to perform manual Gaussian fitting. The resulting measurements form the final source catalogue used in the following sections to analyse

the properties of the detected radio sources and their association with methanol masers.

3.3 RESULTS

This section presents the outcome of the pilot survey and evaluates the nature of the detected high-frequency radio sources. The aim is to determine which of these detections are genuinely associated with young HII regions, and to identify the most suitable candidates for higher-resolution follow-up. The analysis begins with an initial classification based on positional associations with well-known tracers of high-mass star formation, before progressively refining the sample using a series of complementary diagnostics.

3.3.1 INITIAL INSPECTION AND CLASSIFICATION

The source extraction described in Section 3.2.3 produced a catalogue of 68 high-frequency radio detections at 23.7 GHz observed across 128 fields covering 141 MMB methanol masers. Basic source properties, including position, flux density, and fitted size, are listed in Table 3.2. The first step is therefore to assess which of these detections are likely to be physically associated with embedded massive star formation, and which are more likely unrelated or more evolved sources.

Radio continuum emission at these frequencies can arise from a range of astrophysical mechanisms, such as HII regions, thermal jets, or stellar winds, and therefore positional coincidence with a methanol maser alone is not sufficient to establish the nature of a source. To guide the initial classification, the detected 23.7 GHz emission was compared with several well-established tracers of high-mass star formation: 6.7 GHz methanol masers from the MMB survey (Caswell, 2010; Green et al., 2010; Caswell et al., 2011), 870 μm dust emission from ATLASGAL, and 5 GHz radio continuum counterparts from existing surveys (Table 3.3; Becker et al. 1994; Urquhart et al. 2007, 2009; Purcell et al. 2013; Irabor et al. 2023). Representative examples of these associations are shown in Figure 3.4.

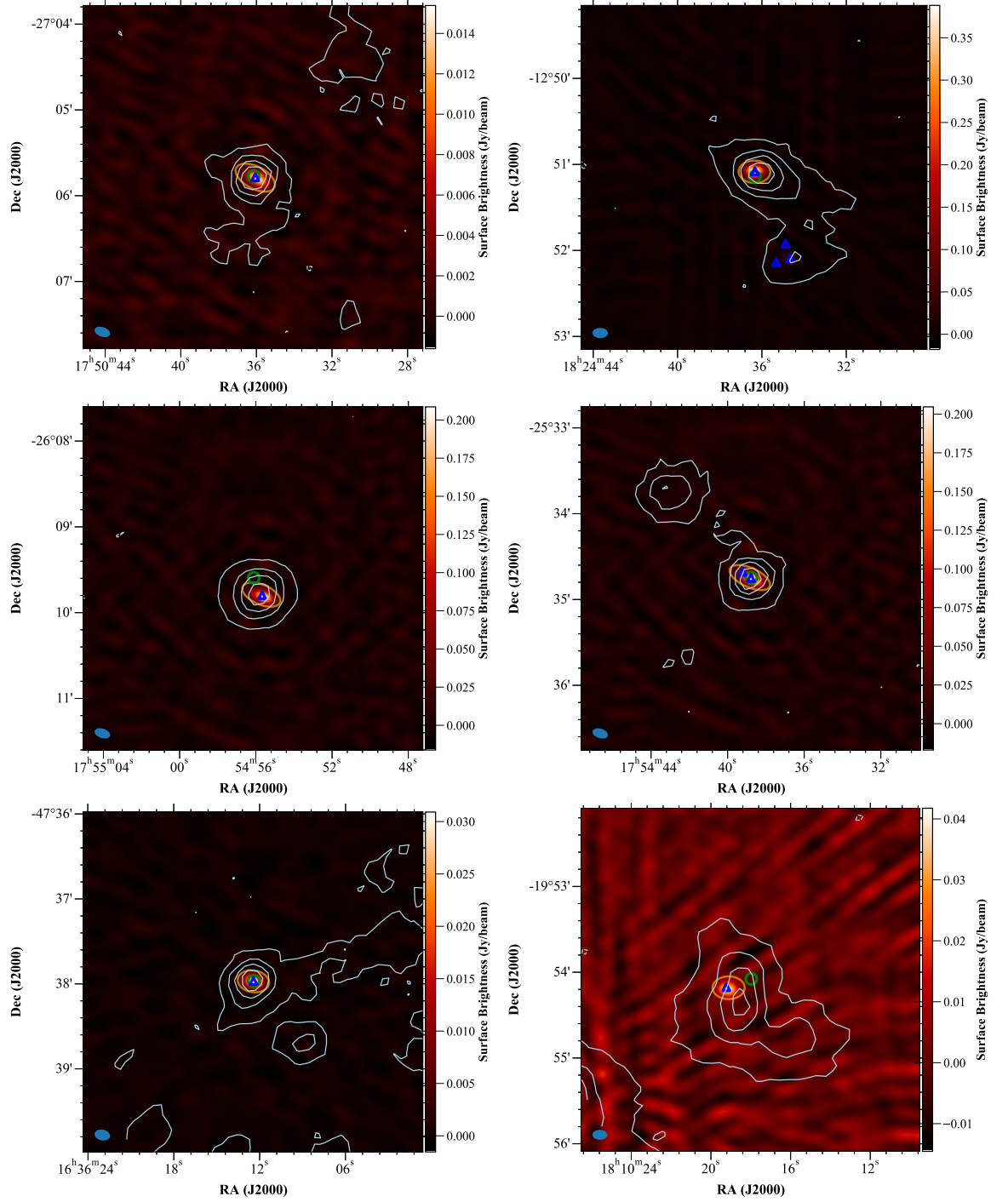


FIGURE 3.4: Examples of high-frequency radio detections. The orange ellipse shows the fitted radio source, the green circles mark the methanol maser positions, and the blue triangles show any low-frequency (5 GHz) radio counterparts. Grey contours trace the 870 μm dust emission from ATLASGAL (Schuller et al., 2009). The blue ellipse in the lower-left corner shows the beam size and orientation.

TABLE 3.3: Observational parameters for the archival 5 GHz catalogues used to compare and calculate the spectral index measurements.

Catalogue	Synthesised beam (arcsec)	Sensitivity rms (mJy beam ⁻¹)	Largest angular scale (arcsec)	Reference
Magpis	5	0.30	100	(1)
CORNISH–North	1.5	0.43	14	(2)
CORNISH–South	2.5	0.11	40	(3)
RMS	1.5–2.5	0.32	20	(4)

References. (1) Becker et al. (1994), (2) Purcell et al. (2013), (3) Irabor et al. (2023), (4) Urquhart et al. (2007).

Each field was inspected visually to assess whether the 23.7 GHz detections were positionally coincident with these tracers. The fitted radio ellipse provided a guide to the location and extent of the radio source, while the angular separations between the radio emission and the nearest methanol maser, dust clump, and 5 GHz source were quantified more explicitly in Figure 3.10. The overall pattern of associations is summarised in the Venn diagram shown in Figure 3.5.

The initial cross-matching reveals a useful separation within the sample. Fourteen of the 68 radio sources are associated with both dust emission and methanol masers, but have no detected 5 GHz counterpart. Since three of these lie outside the available 5 GHz survey coverage, the remaining 11 sources appear as candidates for very young, compact, or optically thick HII regions. These are discussed in more detail later in the chapter. A further 25 sources are associated with both 23.7 GHz and 5 GHz emission and are more likely to represent somewhat more evolved UC HII regions. Fifteen additional sources are associated with dust and 5 GHz radio emission but show no corresponding methanol maser emission, consistent with more evolved HII regions in which the conditions required for methanol maser emission have been disrupted (e.g., through the dispersal of molecular gas).

Fifty-four of the 68 radio detections are immediately associated with tracers expected for HII regions, leaving 14 sources whose nature is less certain. One of these, G019.491+0.135, has a steep negative spectral index ($\alpha = -1.33 \pm 0.06$) and no associated dust or infrared emission, making an extragalactic origin the most likely interpretation. Seven sources are associated only with dust emission and were investigated further using three-colour images constructed from the 4.5, 5.8, and 8.0 μm IRAC bands

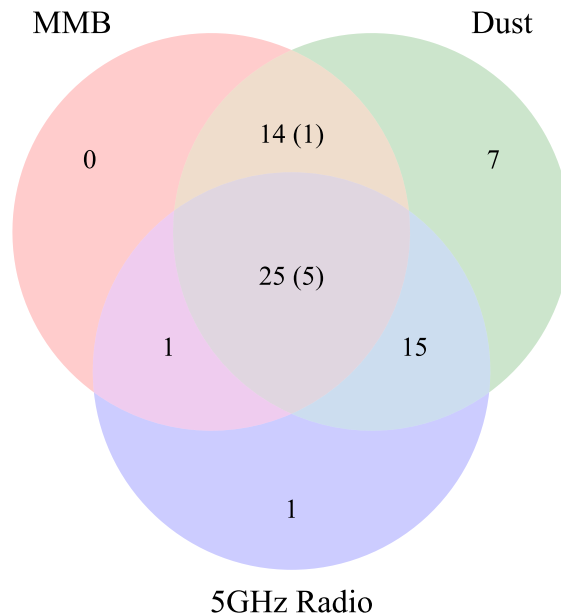


FIGURE 3.5: Venn diagram showing associations between high-frequency radio sources, methanol masers, ATLASGAL dust clumps, and 5 GHz radio sources. Five high-frequency detections lack any star-forming tracer. Numbers in parentheses show water maser counts associated with 6.7 GHz methanol masers.

of the GLIMPSE survey (Fazio et al., 2004; Benjamin et al., 2003), maps of which are shown in Figure 3.6.

The infrared morphologies of these seven dust-only detections suggest a mixed population. Classification was based on the mid-infrared structure and brightness of each source. Extended HII regions are typically identified by their diffuse, large-scale emission, often exhibiting irregular or shell-like morphologies. In contrast, compact and ultra-compact HII regions appear as bright, localised sources with relatively simple, symmetric structures. Photodissociation regions (PDRs) are characterised by extended emission at $8\mu\text{m}$ tracing the boundaries between ionised and molecular gas, often forming filamentary or arc-like structures. YSOs where present, are generally identified as point-like or compact infrared sources embedded within dust emission.

Two sources appear to be extended HII regions (G012.632−0.017 and G014.986−0.122), while one is more consistent with a compact UC HII region (G014.599+0.020). Two sources correspond to PDRs (G331.334−0.335 and G332.644−0.607), based on their extended $8\mu\text{m}$ emission and lack of compact radio counterparts. One source is likely extragalactic (G003.307−0.403), and one may be a pulsar candidate (G332.098−0.419). Another source, G331.542−0.067, shows radio and infrared emission consistent with

an evolved HII region located at the edge of a PDR. The remaining five radio detections lack any associated star-formation tracer and are most naturally interpreted as extragalactic background sources.

Overall, this initial classification identifies 58 sources as likely HII regions, two as PDRs, seven as likely extragalactic radio sources, and one as a potential pulsar candidate. This indicates that the majority of the detected high-frequency continuum sources are associated with massive star formation. Sources not associated with HII regions are excluded from further analysis, allowing the remainder of this section to focus on a cleaner and more physically meaningful sample of candidate HII regions.

3.3.2 REFINING THE HII REGION SAMPLE

The initial classification provides a useful first separation between likely HII regions and more ambiguous sources, but a more robust assessment is required before identifying the strongest HC HII region candidates. In this subsection, the remaining radio sources are examined using several complementary diagnostics: comparison with published ATLASGAL classifications, positional agreement with well-established tracers of high-mass star formation, water maser associations, and radio spectral indices. These tests help to distinguish genuinely embedded HII regions from sources whose radio emission is more likely to arise from extended, complex, or unrelated structures.

3.3.2(a) COMPARISON WITH ATLASGAL CLUMP CLASSIFICATIONS

As a first consistency check, the candidate HII regions were compared with the classifications assigned to their host clumps by the ATLASGAL team (Urquhart et al., 2014b, 2018, 2022). This provides an independent test of whether the sources identified here are associated with clumps already recognised as embedded HII regions, while also highlighting cases where the host clump has instead been classified as protostellar or YSO-like. Such sources are of particular interest in the present study, since they may represent an earlier stage of evolution prior to the development of a well-established UC HII region.

The distribution of ATLASGAL classifications is shown in Figure 3.8. Most of

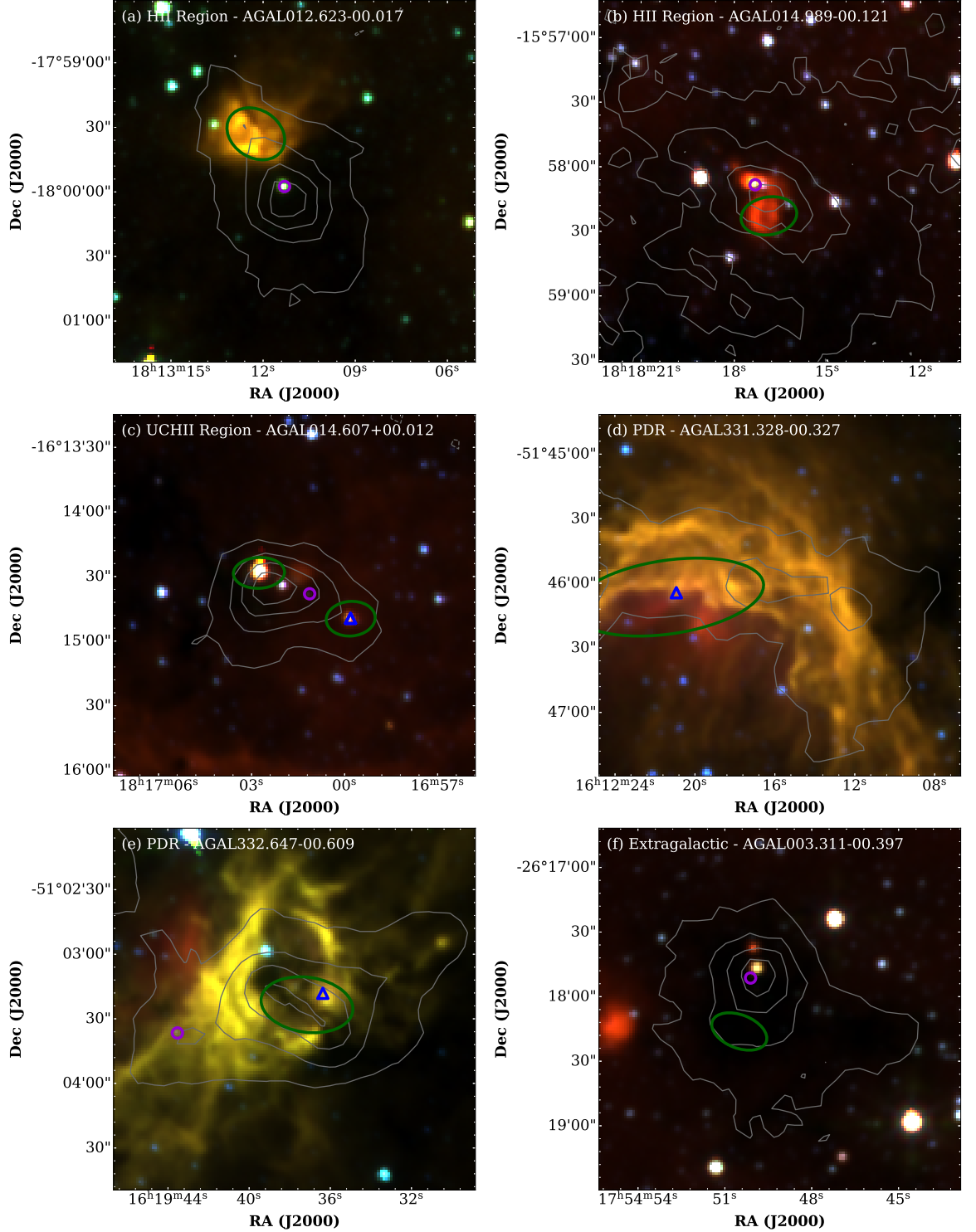


FIGURE 3.6: Three-colour images of eight radio sources associated with dust emission or ambiguous infrared morphology. Seven panels show dust-associated radio sources lacking methanol masers, while one panel (f) shows the likely extragalactic source G003.307–0.403. The images utilise the 4.5, 5.8 & 8.0 μm IRAC bands from the GLIMPSE survey. The green ellipse marks the position of the high-frequency (23.7 GHz) radio source, while the purple circles indicate the positions of the methanol masers. Blue triangles show the positions of the low-frequency (5 GHz) radio counterparts, and grey contours trace the 870 μm dust emission from ATLASGAL.

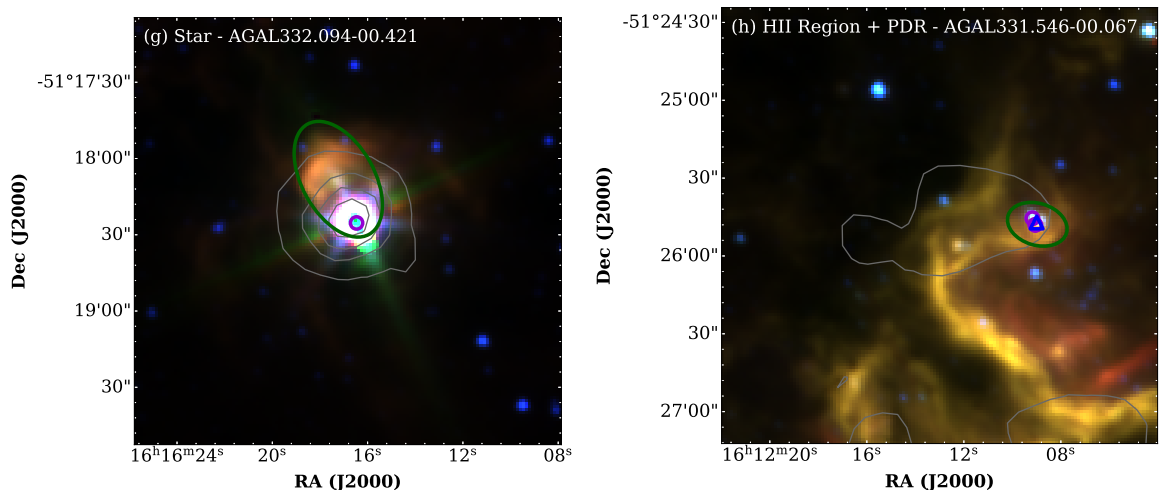


FIGURE 3.6: Continued.

the host clumps are already classified as HII regions, with 37 sources corresponding to 64.3 per cent of the sample. This is broadly consistent with the interpretation based on the radio, dust, and mid-infrared data presented above. Of greater interest here are the sources whose host clumps remain classified as protostellar or YSO objects, since these have not previously shown the defining characteristics of established UC HII regions and may represent younger systems. In total, three host clumps are classified as protostellar and eight as YSOs, giving 11 objects that are especially relevant as candidate compact and optically thick HII regions.

Not all of the initially classified radio sources fit this picture as cleanly. Six are classified by ATLASGAL as PDRs, while three are associated with complex mid-infrared morphologies that make a firm classification uncertain. Inspection of these fields indicates that the radio emission is more likely associated with larger-scale or morphologically complex structures than with compact embedded HII regions.

Two representative examples are shown in Figure 3.7. G316.363–0.362 shows extended radio emission that is clearly offset from the central methanol maser and the peak of the ATLASGAL dust emission (AGAL316.361–00.362; see panel a of Fig. 3.7). The morphology is inconsistent with a compact, centrally embedded ionising source and instead suggests emission associated with a more extended or evolved structure. Similarly, G331.279–0.190 (AGAL331.279–00.189) exhibits elongated and spatially extended radio emission that traces larger-scale emission rather than a compact source, as also indicated by the fitted radio ellipse (see panel b of Fig. 3.7).

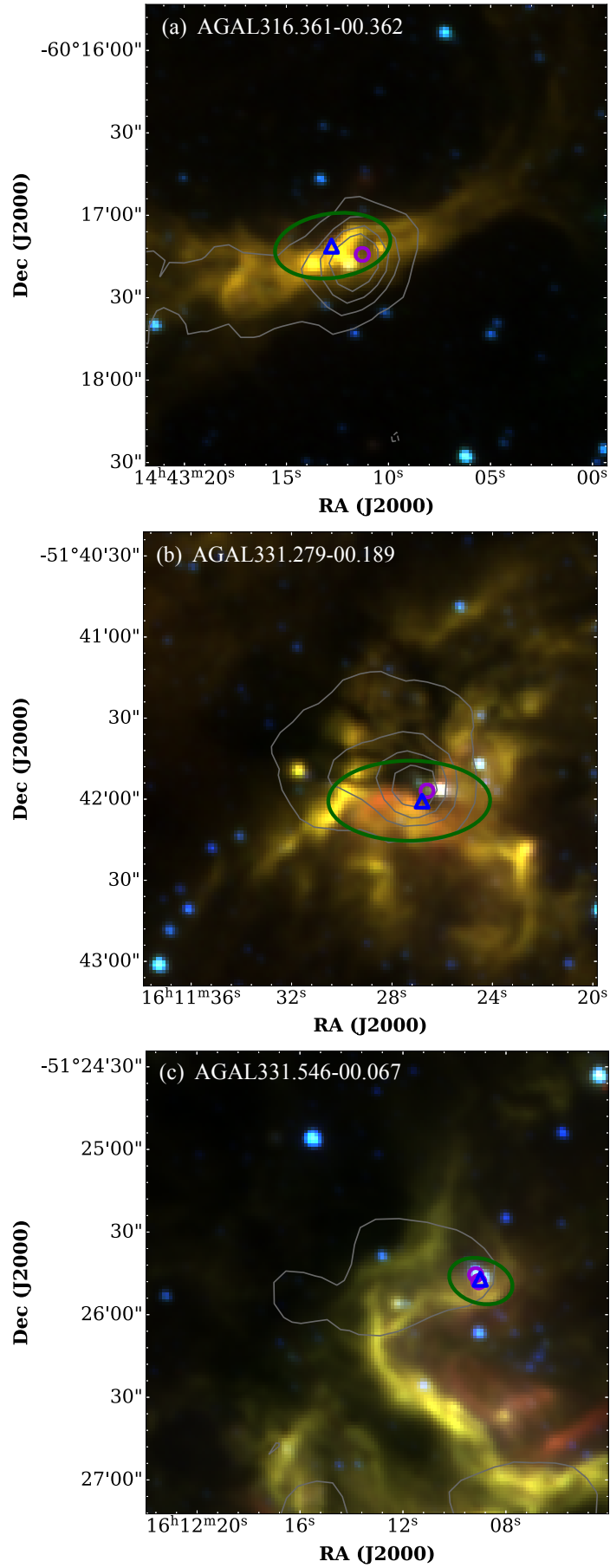


FIGURE 3.7: Example GLIMPSE mid-infrared images of sources that required additional inspection due to their complex or ambiguous morphology. From top to bottom: (a) G316.363–0.362, (b) G331.279–0.190, and (c) G331.542–0.067. The symbols are the same as in Figure 3.4.

In both cases, the lack of a compact, centrally peaked morphology and the spatial offset from the expected star-forming core argue against an interpretation as a compact or hypercompact HII region. These characteristics are more consistent with emission arising from PDRs or evolved HII regions, where ionised gas is distributed over larger spatial scales and is no longer centrally concentrated on the embedded protostar. These nine sources are therefore excluded from further analysis.

After excluding these nine sources, the working sample is reduced to 49 HII region candidates. This includes G331.542–0.067 (AGAL331.546–00.067), which is retained despite not being clearly associated with a compact ATLASGAL clump. In this case, the dust emission is relatively weak and the radio emission is offset from the dust peak; however, the high-frequency (23.7 GHz) emission, low-frequency (5 GHz) counterpart, and methanol maser are all spatially coincident within the uncertainties (see panel c of Fig. 3.7). This strong multi-wavelength association suggests that the source may still represent an embedded object, potentially located at the edge of a PDR or within a disrupted environment. Given this ambiguity, the source is retained for further analysis, with higher-resolution observations required to determine its true nature.

3.3.2(b) EFFECT OF HIGHER-NOISE FIELDS ON THE REFINED SAMPLE

As discussed in Section 3.2, 31 of the 128 observed fields have rms noise values greater than five times the median field rms. Since the source detection threshold is defined relative to the local rms, these higher-noise fields could in principle bias the final sample towards brighter radio sources. To test this directly, the properties of the full refined HII region sample were compared with those obtained after excluding sources located in higher-noise fields.

Of the 49 refined HII region candidates, 15 are located in higher-noise fields. Histograms were constructed for the peak flux density, integrated flux density, and bolometric luminosity of the host clump, and the full sample was compared with the sample excluding these 15 sources. The resulting distributions are shown in Figure 3.9.

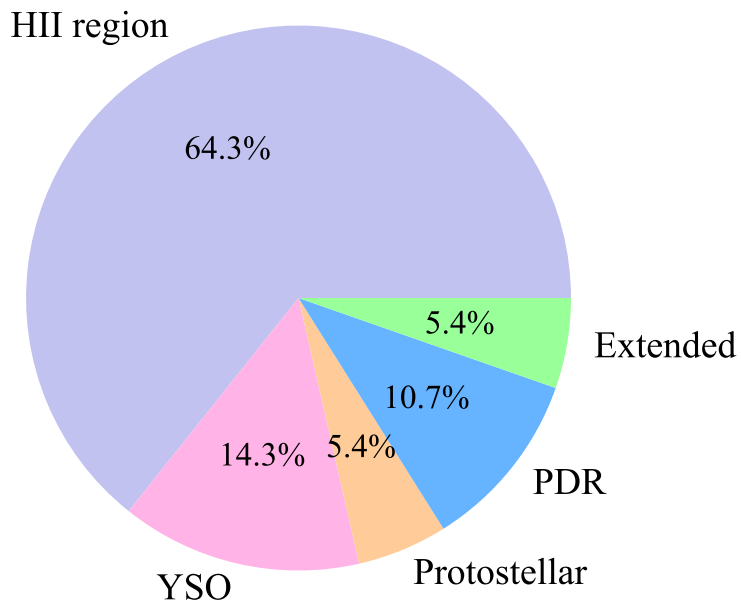


FIGURE 3.8: Distribution of the ATLASGAL classifications for clumps associated with the high-frequency radio sources classified as HII region candidates in Section 3.3.

Two-sample Kolmogorov–Smirnov (KS) tests were also performed to quantify any differences between the distributions, giving p -values of 0.10 for the peak flux density, 0.07 for the integrated flux density, and 0.52 for the bolometric luminosity.

The distributions remain broadly similar after excluding the higher-noise fields. The clump luminosity distributions show particularly strong agreement, while the flux-density distributions exhibit only a mild reduction in the number of faint sources when the higher-noise fields are removed. This behaviour is consistent with the expectation that noisier maps reduce sensitivity to the faintest compact detections, but do not substantially alter the overall properties of the refined compact HII region sample.

Overall, these results indicate that the inclusion of the higher-noise fields does not introduce a significant bias into the final compact HII region catalogue or the main conclusions drawn from this sample.

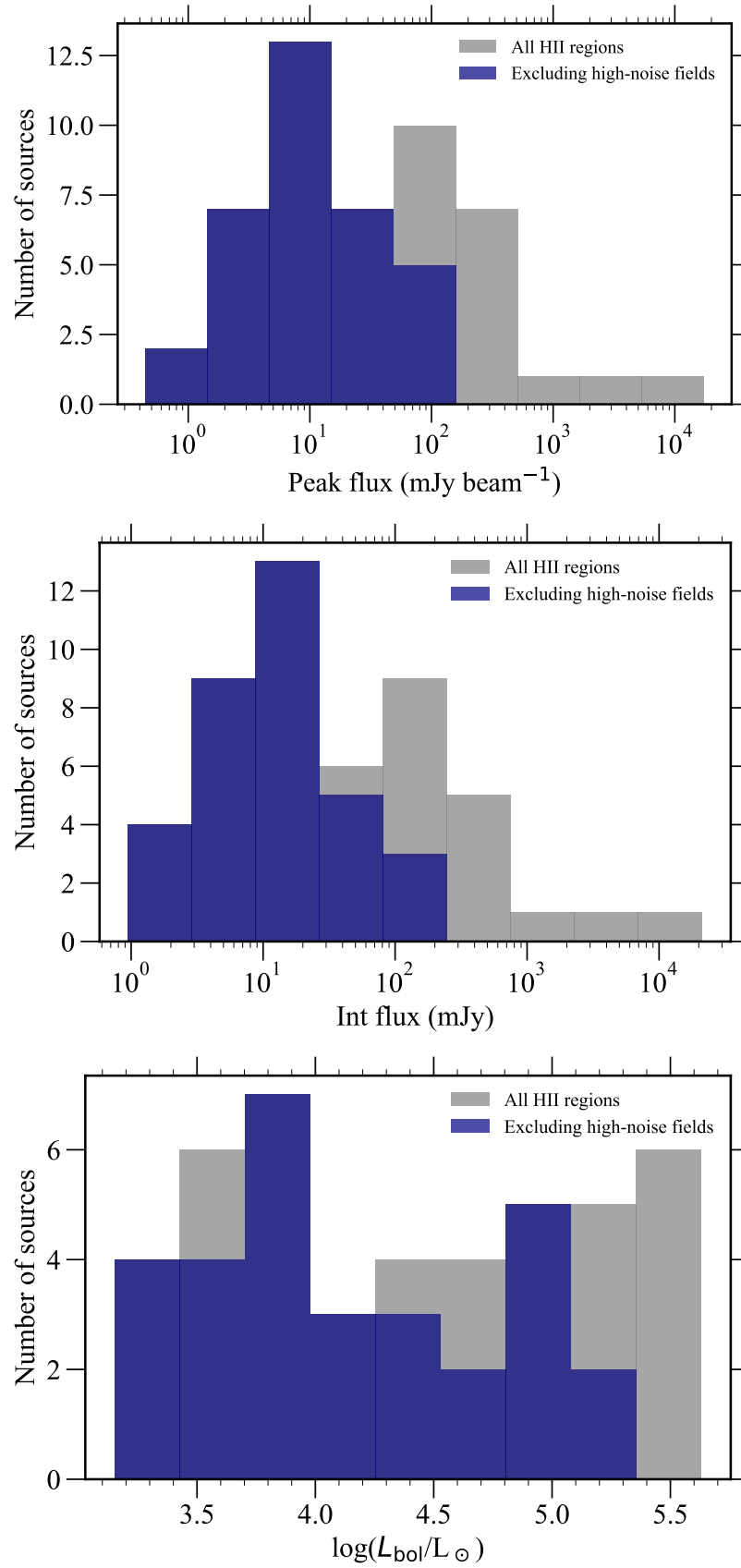


FIGURE 3.9: Histograms comparing the full refined HII region sample with the same sample after excluding sources located in higher-noise fields. The top, middle and bottom panels show peak flux density, integrated flux density, and bolometric luminosity of the host clump, respectively.

3.3.2(c) POSITIONAL CONSISTENCY OF THE STAR FORMATION TRACERS

Because the initial classifications relied partly on visual inspection of the radio and infrared images, it is important to verify that these associations are also supported quantitatively. Figure 3.10 shows the angular offset distributions between the 23.7 GHz radio sources and their nearest ATLASGAL dust clump, MMB methanol maser, and 5 GHz radio counterpart.

All three distributions show strong peaks at small angular separations, indicating that the radio sources are typically located very close to their associated tracers. In each case, the majority of sources lie within only a few arcseconds of their nearest counterpart, with very few sources found beyond the 3σ threshold.

This behaviour is expected for genuine associations, where the positions of the sources should agree to within the measurement uncertainties. These uncertainties introduce small, random offsets, producing a concentration of sources at low separations. In contrast, unrelated sources would be distributed more randomly across the field, resulting in a broader and flatter distribution without a clear peak. The radio–MMB and radio–5 GHz distributions decline particularly steeply, indicating that the high-frequency radio emission is typically well aligned with both the methanol maser and the lower-frequency radio counterpart. The radio–ATLASGAL distribution is broader because the dust emission traces the larger-scale molecular clump rather than the compact ionised gas itself. This effect is amplified by the lower angular resolution of the ATLASGAL data (~ 20 arcsec), compared to the ~ 1 arcsec resolution of the radio and maser observations. As a result, the dust emission appears more extended and naturally produces larger positional offsets.

Only one radio–ATLASGAL association has an angular offset greater than 18 arcsec. This is the source G336.990–0.025, where the radio emission lies near the edge of the dust clump rather than close to its centre (see panel a of Fig. 3.11). The source is extended in the mid-infrared, has a 5 GHz counterpart, and is not associated with a methanol maser. This morphology is consistent with a more evolved structure in which the ionised gas is no longer centrally embedded, and the source is therefore

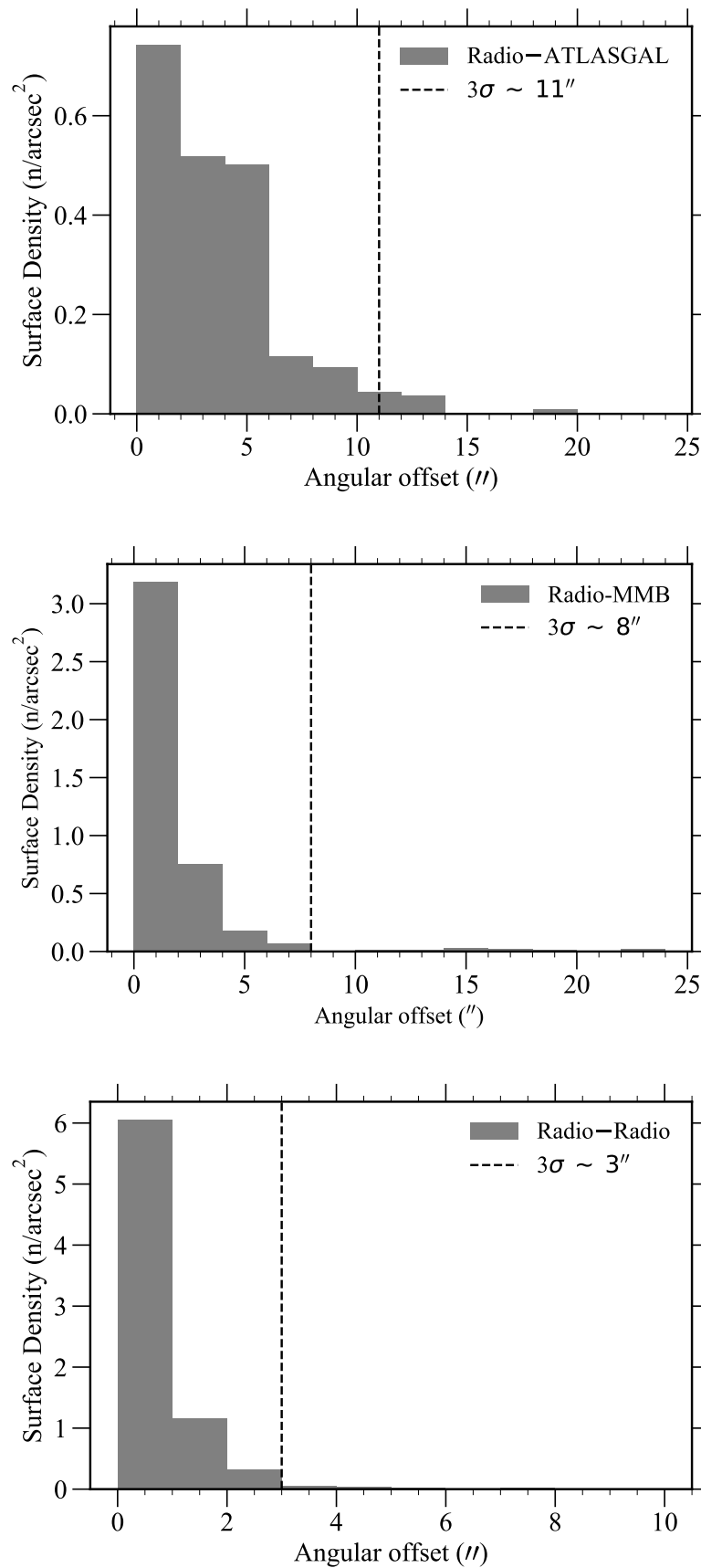


FIGURE 3.10: Histograms of the angular separation between detected radio sources at 23.7 GHz and their nearest ATLASGAL dust clump (top panel), MMB maser (middle panel), and 5 GHz radio counterpart (bottom panel). The top and middle panels use a bin size of 2 arcsec, while the bottom panel uses a bin size of 1 arcsec. The dotted line shows the 3σ radial cut-off for each panel, respectively.

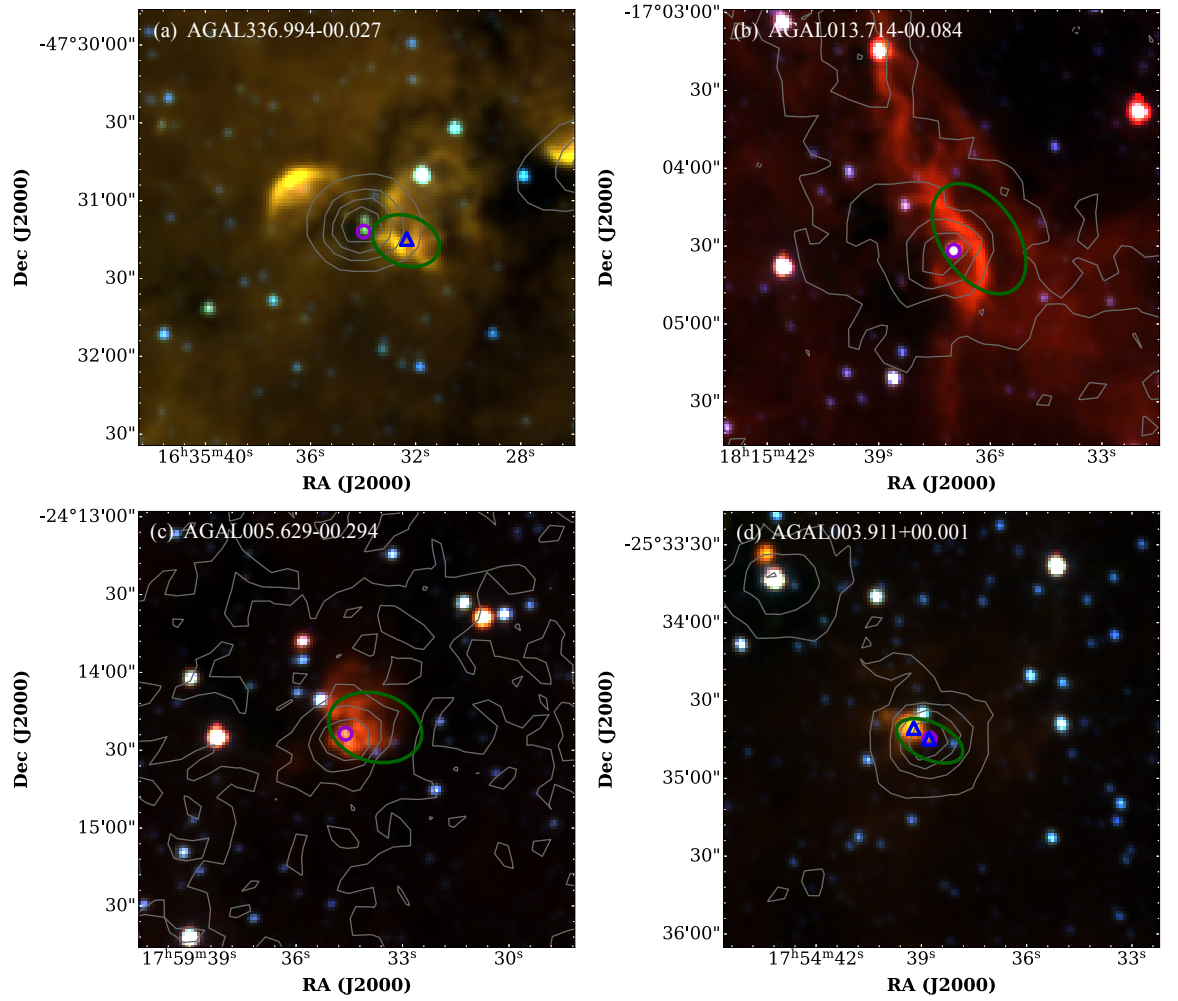


FIGURE 3.11: GLIMPSE MIR maps illustrating positional offset cases discussed in the text. From top left to bottom right: (a) AGAL336.994–00.027, (b) AGAL013.714–00.084, (c) AGAL005.629–00.294, (d) AGAL003.911+00.001. Symbols are the same as in Figure 3.4.

excluded from further analysis.

Among the 23.7 GHz–MMB associations, two sources have offsets greater than 8 arcsec, corresponding to more than 3σ . In both cases, the radio emission is extended and the methanol maser lies near the edge of the radio source (see panels b and c of Figure 3.11). Although the positional offsets are comparatively large, the source morphology suggests that these associations remain physically meaningful, and both sources are retained as HII region candidates.

There is also one 23.7 GHz–5 GHz association with an offset greater than 3 arcsec. In this case, two 5 GHz sources lie within the high-frequency radio ellipse, with offsets of 0.6 and 7.9 arcsec, respectively (Becker et al., 1994). The more distant source is unlikely to be the true counterpart (see panel d of Fig. 3.11), and once it is excluded the positional agreement between the high- and low-frequency radio data is again very good, with all retained matches lying within 3 arcsec.

Overall, these offset distributions provide strong quantitative support for the visual classifications and demonstrate that the majority of the identified associations are robust.

3.3.2(d) WATER MASER ASSOCIATIONS AS AN INDICATOR OF EVOLUTIONARY STAGE

The presence or absence of water maser emission provides a further diagnostic of the evolutionary stage of the candidate HII region sample. Unlike methanol masers, which are radiatively pumped, water masers are collisionally pumped and are commonly associated with shocked gas, for example at the interface between an outflow and the surrounding molecular material (Walsh et al., 2011). In the survey of Titmarsh et al. (2014, 2016), 323 MMB methanol maser sites were searched for water maser emission, yielding an overall methanol–water association rate of approximately 48 per cent, corresponding to ~ 155 sources within a 3 arcsec radius.

The same dataset can be used to assess how frequently water masers are found towards the radio continuum sources identified here. Adopting the same angular offset criterion as for the 23.7 GHz–MMB associations (Figure 3.10), we find that 48 are

associated with both a methanol maser and an HII region, and six are also associated with water maser emission within 8 arcsec.

Five of these water masers are associated with methanol masers, $870\,\mu\text{m}$ dust emission, and 5 GHz radio emission, while one source is associated only with methanol maser and dust emission. This corresponds to a water-maser association rate of approximately 12 per cent among the methanol-maser-associated radio continuum sources. This is substantially lower than the overall incidence of water masers towards methanol maser sites and suggests that water maser activity becomes less common once a detectable HII region has formed. A plausible explanation is that the expansion of the ionised nebula disrupts the dense circumstellar gas required for water maser excitation. In this sense, the water masers appear to trace an earlier phase of massive star formation than the compact radio continuum sources identified here (Deacon et al., 2007; Urquhart et al., 2022).

Two of the strongest HC HII region candidates identified later in this section, G005.885–0.392 and G018.735–0.227, are associated with both methanol and water masers and are discussed individually in Appendix 7.1.1.

3.3.2(e) SPECTRAL INDICES AND THE IDENTIFICATION OF OPTICALLY THICK CANDIDATES

Having established the likely evolutionary stage of the sample through associations with common tracers of star formation, the next step is to examine the physical properties of the ionised gas itself. In particular, it is important to determine whether any of the sources remain optically thick at centimetre wavelengths, as expected for the youngest and most compact HII regions.

This can be tested using the radio spectral index. Of the 48 candidate HII regions identified above, 32 are detected at both 23.7 GHz and 5 GHz, allowing a direct comparison of their flux densities across this frequency range. The spectral index therefore provides a way to distinguish between optically thin and optically thick free-free emission.

In a typical UC HII region, the turnover frequency occurs at around ~ 5 GHz

(Beltrán et al., 2007; Keto & Klaassen, 2008; Hoare et al., 2007). At higher frequencies, the emission becomes optically thin, resulting in a relatively flat spectrum with $\alpha \simeq -0.1$. In contrast, HC HII regions are expected to remain optically thick over a broader frequency range and show rising spectra, with $\alpha \simeq 1-2$ (Kurtz, 2005b). The spectral index is a direct observational indicator of whether a source is still optically thick between 5 and 23.7 GHz, and hence a key diagnostic for identifying the youngest objects in the sample.

The spectral index is calculated using

$$\alpha = \frac{\ln(S_{23.7 \text{ GHz}}/S_{5 \text{ GHz}})}{\ln(23.7/5)}, \quad (3.1)$$

where S_ν is the flux density at frequency ν . (see Section 2.1.2 for details) The corresponding uncertainty is

$$\Delta_\alpha = \frac{\sqrt{(\sigma_{23.7 \text{ GHz}}/S_{23.7 \text{ GHz}})^2 + (\sigma_{5 \text{ GHz}}/S_{5 \text{ GHz}})^2}}{\ln(23.7/5)}, \quad (3.2)$$

where σ_ν is the uncertainty in the measured flux density.

In practice, reliable spectral indices can only be derived for compact sources with well-defined flux measurements at both frequencies. Extended emission is more susceptible to spatial filtering in interferometric observations, which can lead to inconsistent flux recovery between datasets. To minimise these effects, a simple compactness criterion was applied using the ratio of integrated to peak flux density (y-factor; $f_{\text{int}}/f_{\text{peak}}$), and the analysis was restricted to sources with a y-factor less than 2. In addition, the mid-infrared morphology of each source was examined, since diffuse or complex structures are more likely to be affected by resolution and filtering differences.

Based on these criteria, 15 sources were found to be too extended for reliable spectral index analysis and were excluded. This leaves a sample of 19 compact HII regions with robust measurements at both frequencies.

Although the largest angular scales recovered by the 5 GHz surveys ($\sim 15-30$ arcsec) are broadly comparable to those in the 23.7 GHz data (~ 20 arcsec), the beam sizes differ significantly. To reduce the impact of this mismatch, the peak flux density at 23.7 GHz ($\theta_{\text{beam}} \sim 10$ arcsec) and the integrated flux density at 5 GHz ($\theta_{\text{beam}} < 5$ arcsec) are

used for all compact sources. In cases where multiple 5 GHz components fall within the 23.7 GHz beam, the integrated 5 GHz fluxes are summed before calculating the spectral index.

As a consistency check, flux densities were also measured directly from the 5 GHz images for sources covered by more than one survey. These measurements agree with the catalogue values to within 10 per cent, and a comparison of sources with counterparts in both CORNISH and MAGPIS shows no significant systematic differences. This suggests that spatial filtering at 5 GHz does not strongly bias the derived spectral indices.

For sources detected at 23.7 GHz but lacking a 5 GHz counterpart, it is still possible to estimate a lower limit to the spectral index using the 5 GHz noise level. Following Yang et al. (2019), this is given by

$$\alpha_{\min} = \frac{\ln[(S_{23.7\text{ GHz}} - 3\text{ d}S_{23.7\text{ GHz}})/(3\text{ d}S_{5\text{ GHz}})]}{\ln(23.7/5)}, \quad (3.3)$$

where $\text{d}S_\nu$ is the uncertainty in the flux density at frequency ν . Here, $\text{d}S_{23.7\text{ GHz}}$ is measured from emission-free regions of the 23.7 GHz maps, while $\text{d}S_{5\text{ GHz}}$ is taken from the corresponding 5 GHz data. This approach assumes a 3σ upper limit at 5 GHz and subtracts 3σ from the measured 23.7 GHz flux density, providing a conservative lower bound on the spectral index. An example is shown in Figure 3.12.

In total, spectral index measurements or lower limits were obtained for 28 compact HII regions: 19 reliable measurements and 9 lower limits (Table 3.4). The resulting distribution is shown in Figure 3.13. The histogram is strongly peaked around $\alpha \sim 0$, indicating that the majority of the sample is consistent with optically thin free-free emission, as expected for typical HII regions.

Within this distribution, the sources of greatest interest are those that depart from this behaviour. In particular, objects that are mid-infrared point-like or mid-infrared quiet and that also exhibit positive spectral indices are strong candidates for remaining optically thick between 5 and 23.7 GHz.

All but seven sources show either flat or positive spectral indices, consistent with expectations for HII regions. Of the 28 compact radio sources considered here, 13 have

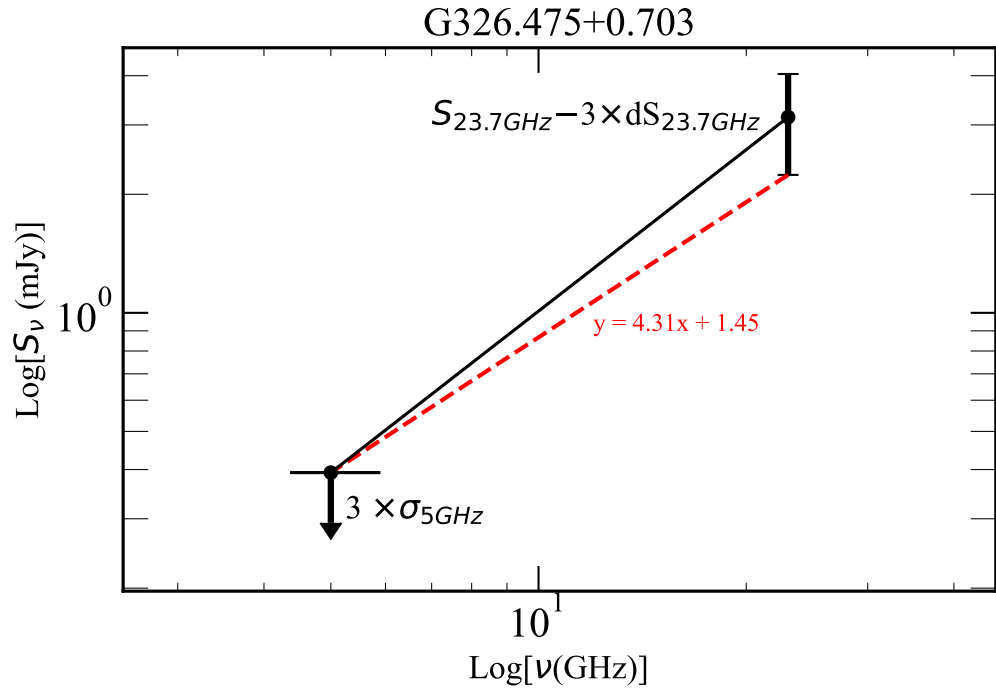


FIGURE 3.12: Flux density measurements for G326.475+0.703 as a function of frequency. The plot shows the measured 23.7 GHz flux density and the 5 GHz upper limit determined from the 3σ rms noise. The error bar on the 23.7 GHz flux is 3σ . The red line shows the linear fit used to derive the lower limit to the spectral index.

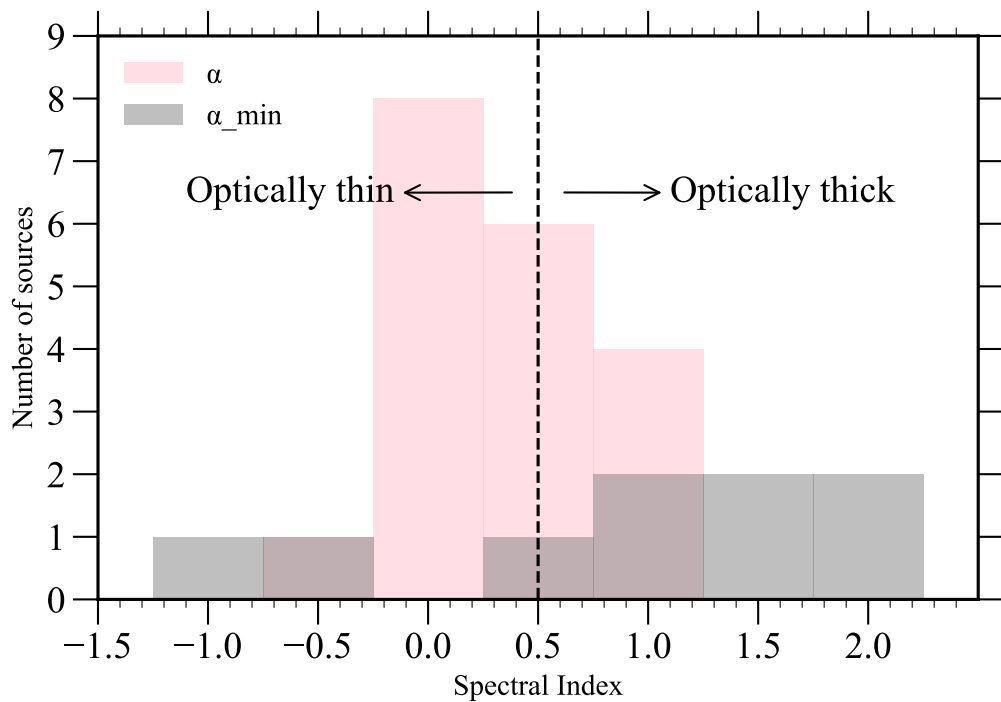


FIGURE 3.13: Histogram showing the distribution of measured spectral indices (pink) and lower limits (grey). Reliable spectral indices were obtained for 19 sources and lower limits for 9 sources. The data are binned with a bin size of 0.50. The dashed line indicates the approximate threshold between optically thin and optically thick nebulae.

TABLE 3.4: Spectral index and lower limit measurements for the compact high-frequency radio detections with 5 GHz coverage. For sources with more than one 5 GHz counterpart, the average offset and size are given and indicated with an †. The 5 GHz upper limits are quoted as 3σ thresholds.

Radio name	f_{int} 5 GHz (mJy)	Δf_{int} 5 GHz (mJy)	Observed 5 GHz size (arcsec)	f_{peak} 23.7 GHz (mJy beam $^{-1}$)	Δf_{peak} 23.7 GHz (mJy beam $^{-1}$)	23.7 GHz Offset (arcsec)	α	$\Delta\alpha$	Reference catalogue
G002.143+0.009	5.7	0.2	1.5	6.6	0.29	0.41	0.096	0.023	(1)
G002.614+0.134†	120	0.78	7.0	170	7.8	1.7	0.21	0.019	(1)
G003.438−0.349	94	0.41	2.3	94	2.8	0.67	0.00054	0.013	(1)
G003.910+0.001†	37	0.34	1.9	93	3.1	3.7	0.58	0.014	(1)
G004.680+0.277	5.4	0.54	5.2	9.8	0.31	1	0.39	0.043	(1)
G005.885−0.392	2200	1.4	3.3	7900	230	0.56	0.81	0.012	(1)
G011.904−0.141†	42	1.8	3.6	76	2.0	1.6	0.38	0.02	(2)
G012.112−0.127	< 1.2			0.68	0.06		> -0.96		(2)
G014.229−0.510	< 1.0			1.5	0.34		> -0.31		(2)
G014.599+0.020	4.4	1.1	2.1	6.6	0.12	0.17	0.26	0.1	(2)
G014.610+0.012	< 1.0			6.2	0.27		> 0.86		(2)
G018.461−0.004	340	32	3.1	420	14	0.5	0.13	0.04	(1)
G018.665+0.029	5.7	0.85	2.0	5.5	0.49	0.046	-0.014	0.072	(2)
G326.475+0.703	< 0.39			3.1	0.3		> 1.2		(4)
G327.402+0.445	87	0.31	1.1	120	2.7	0.45	0.23	0.0091	(3)
G331.442−0.187	62	5.4	13	69	1.3	0.36	0.075	0.037	(4)
G331.542−0.067	75	0.55	0.43	330	46	2.2	0.95	0.058	(3)
G331.710+0.604	< 0.6			1.5	0.12		> 0.38		(4)
G332.826−0.549	1300	4.5	3.2	4200	180	0.48	0.78	0.018	(3)
G332.987−0.487	< 0.36			8.0	1.3		> 1.9		(4)
G333.029−0.063	5.6	0.15	2.6	31	1.3	0.57	1.1	0.02	(4)
G336.983−0.183	18	0.25	0.42	56	1.9	1.1	0.73	0.015	(3)
G338.280+0.542	< 0.38			3.8	0.24		> 1.3		(4)
G338.566+0.110	5	0.19	2.8	8.8	0.32	0.77	0.36	0.022	(4)
G338.922+0.624	140	0.21	1.5	190	7.9	0.36	0.17	0.017	(3)
G338.925+0.556	< 0.38			12	1.1		> 2.0		(4)
G339.622−0.121	< 0.42			4.9	0.25		> 1.4		(4)
G339.980−0.539	140	0.65	5.5	52	30	0.79	-0.64	0.24	(4)

References. (1) Becker et al. (1994), (2) Purcell et al. (2013), (3) Urquhart et al. (2007), (4) Irabor et al. (2023).

either a positive spectral index or a lower limit indicative of optically thick emission. These sources are identified as the most promising HC HII region candidates in the sample and are examined in more detail in Section 3.4.

3.3.3 PHYSICAL PROPERTIES OF THE REFINED SAMPLE

Having established the radio characteristics of the sample, the next step is to place these sources within a broader evolutionary framework. In other words, rather than considering the radio emission in isolation, we now examine the properties of the molecular clumps in which these HII regions are embedded.

Of the 141 methanol masers targeted in this study, 99 are associated with distinct ATLASGAL dust clumps. After applying the selection criteria described above, 49 of these clumps are found to host HII regions. For each of these sources, key physical properties, including the bolometric luminosity, FWHM clump mass, and luminosity-to-mass ratio, are taken from the ATLASGAL catalogue (Urquhart et al., 2022). These parameters provide a useful way to assess both the energetic output of the embedded source and the evolutionary state of its natal environment.

Figure 3.14 compares the distributions of these properties for the radio-selected sample with those of the wider ATLASGAL population, separated into protostellar, YSO, and HII region classifications. Visually, the radio-selected sources already appear to occupy a more restricted region of parameter space, but this can be tested more rigorously using a two-sample KS test.

The KS test quantifies the maximum difference between two cumulative distributions and provides a corresponding p -value for the null hypothesis that both samples are drawn from the same parent population. Following the convention adopted throughout this thesis, this null hypothesis is rejected when $p < 0.0013$, corresponding to a 3σ significance level.

Applying this test to the FWHM clump mass distributions shows no significant difference between the radio-selected sample and the general ATLASGAL populations ($p > 0.41$). This indicates that the clump masses themselves are broadly similar, and that the presence of detectable high-frequency radio emission is not strongly dependent

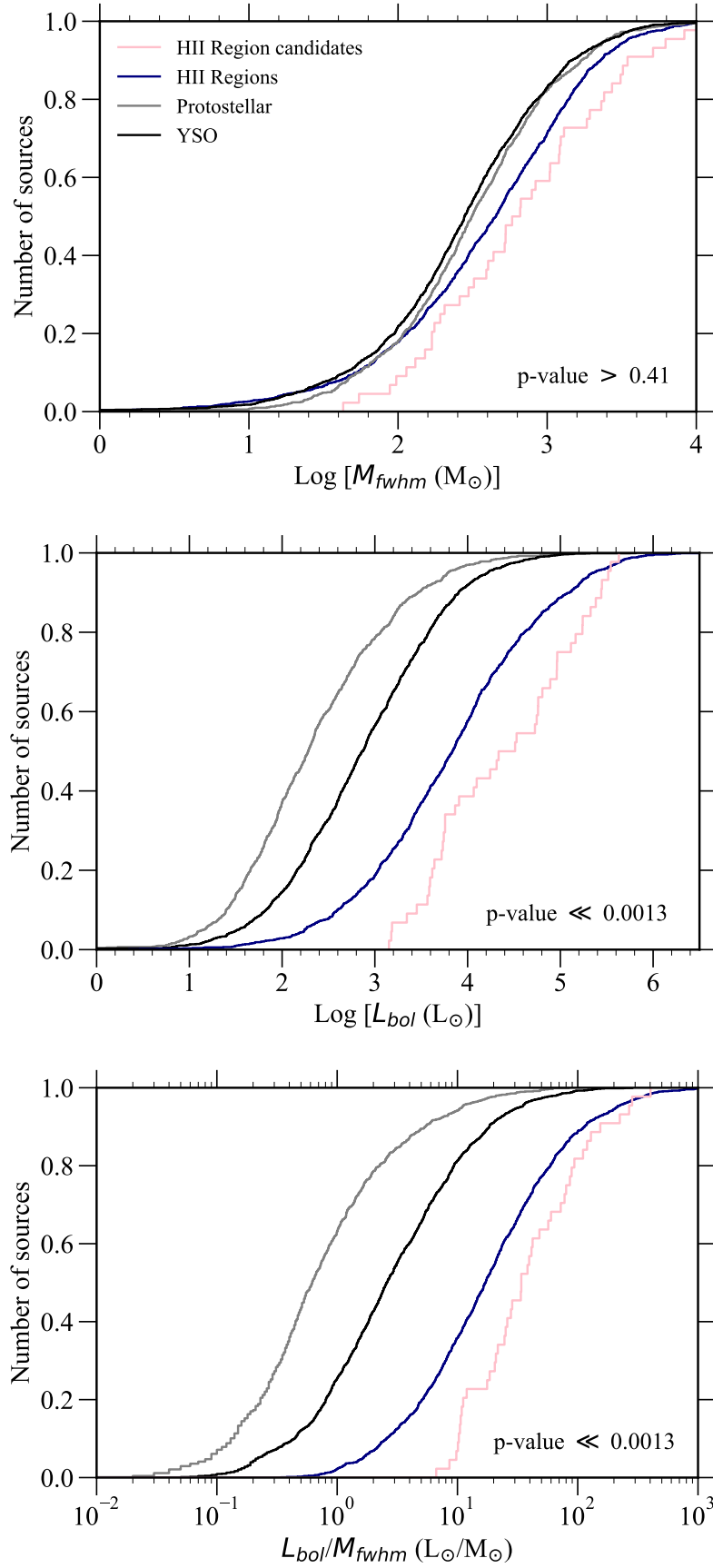


FIGURE 3.14: Cumulative distribution functions for bolometric luminosity (top panel), FWHM mass (middle panel), and L_{bol}/M_{clump} ratio (bottom panel) for the full population of ATLASGAL dust clumps classified as protostellar, YSO, and HII regions. The pink distributions show the sample of 49 HII regions identified here. The p -value from the KS test is given in the lower-left corner of each panel.

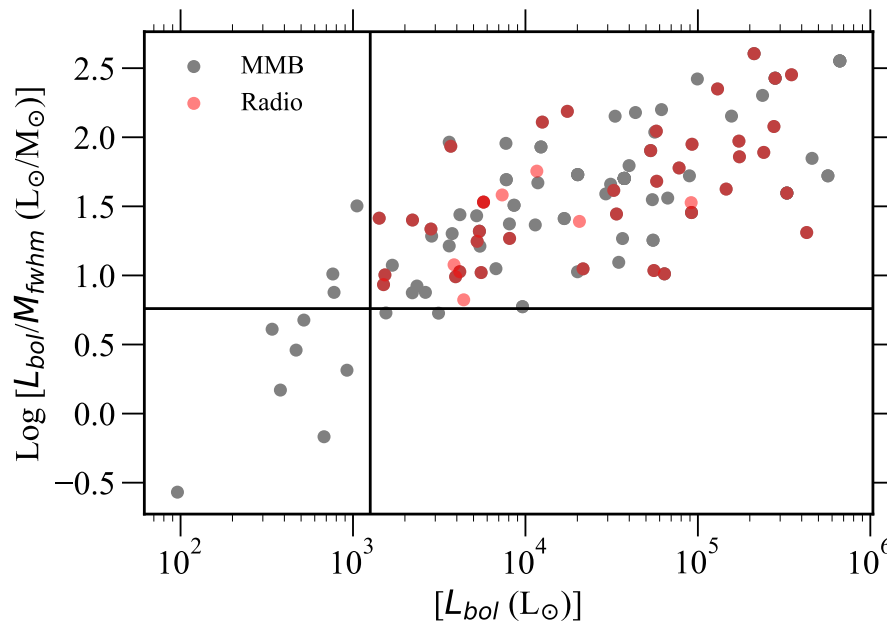


FIGURE 3.15: Bolometric luminosity as a function of luminosity-to-mass ratio for the full population of methanol masers (grey) and the subset associated with high-frequency radio emission (red). Sources offset from the central MMB methanol maser position are shown in pink.

on the total mass of the host clump.

In contrast, both the bolometric luminosity and the luminosity-to-mass ratio show clear and statistically significant differences ($p < 0.0013$ in both cases). These parameters are expected to increase as massive stars evolve, heating and disrupting their surrounding material. The observed shifts therefore indicate that the radio-selected sample is associated with more evolved and more energetically active objects, consistent with the presence of HC HII regions.

This behaviour is illustrated more directly in Figure 3.15, which shows the relationship between bolometric luminosity and luminosity-to-mass ratio for the full methanol maser sample and for the subset associated with high-frequency radio emission. Reliable distance estimates are available for 92 of the 99 ATLASGAL clumps and for 44 of the 49 HII regions identified here.

The radio-selected HII regions are predominantly located in the upper-right quadrant of the figure, above the vertical line at $L_{\text{bol}} = 10^3 L_{\odot}$ and the horizontal line at $L_{\text{bol}}/M_{\text{fw hm}} \approx 5.1 L_{\odot} M_{\odot}^{-1}$. This indicates that they are associated with both high bolometric luminosities and luminosity-to-mass ratios. The lower luminosity boundary

corresponds approximately to that expected from an $\sim 8\text{--}10\text{ M}_{\odot}$ main-sequence star, sufficient to produce a detectable HII region (e.g. Panagia, 1973; Martins et al., 2005), while the upper end of the sample extends to $\sim 10^5\text{ L}_{\odot}$. Together, this range spans sources consistent with mid- to late-B stars at the lower end and extending to late-O type stars at the upper end.

It is also notable that the majority of methanol masers lie within this same region of parameter space, with most sources falling above both threshold lines. This reinforces the well-established connection between methanol masers and high-mass star formation (e.g. Minier et al., 2003; Breen et al., 2013), and shows that the subset associated with high-frequency radio emission represents a natural extension of this population into a later evolutionary phase.

3.3.4 LYMAN CONTINUUM FLUX AND BOLOMETRIC LUMINOSITY

The final step in assessing the nature of the compact radio sources is to compare their Lyman continuum photon flux with their bolometric luminosity. This provides an additional way to test whether the radio emission is more consistent with compact HII regions or with other forms of ionised emission, such as radio jets. For HII regions, these quantities are expected to be closely correlated, as both the radio emission and the infrared luminosity arise from the ionising radiation of the central star. Lyman continuum photons ionise the surrounding gas to produce free-free radio emission, while their absorption by dust grains is reprocessed into infrared emission. In contrast, radio jets are powered by accretion processes and are therefore less directly linked to the stellar luminosity, leading to a weaker or more scattered correlation.

This comparison is important because spectral index measurements alone do not always provide a clear distinction between these objects. As discussed above, both optically thick HII regions and radio jets can show rising radio spectra. However, these two classes of object differ in how their radio luminosity scales with bolometric luminosity. Radio jets follow a shallower relation, whereas HII regions are expected to produce a much stronger ionising flux for a given luminosity. Comparing Lyman continuum flux with bolometric luminosity provides a further check on whether the

sources identified here are genuine compact HII regions.

This question has become particularly relevant in light of the work of Purser et al. (2021), who presented radio observations of 56 massive star-forming regions spanning a range of evolutionary stages. Thermal radio emission was detected towards 94 per cent of their MYSO sample, and 84 per cent of those detections showed jet-like characteristics. In addition, 26 sources had already been classified as ionised jets by Purser et al. (2016). The comparison made here is intended to test whether the compact radio sources in the present sample are more consistent with HII regions than with ionised jets.

The Lyman continuum photon flux, N_i , is calculated following the method described in Section 2.1.2, assuming optically thin free-free emission (Panagia, 1973; Thompson, 1984; Carpenter et al., 1990; Urquhart et al., 2013). For HCHII regions, the emission can remain optically thick below ~ 40 GHz. In this regime, part of the free-free emission is absorbed within the source itself, so the observed flux density does not reflect the total ionising photon output. As a result, the derived Lyman continuum photon flux represents a lower limit to the true value. Only once the emission becomes optically thin does the radio flux provide a reliable measure of the full ionising luminosity (Urquhart et al., 2013).

The resulting distribution is shown in Figure 3.16. For comparison, the expected relation for OB ZAMS stars from Davies et al. (2011) and Martins et al. (2005) is shown, together with the empirical relation followed by radio jets from Purser et al. (2016) and Purser et al. (2021). Lower limits are shown for the HCHII region candidates, since their true Lyman continuum fluxes are likely to be underestimated if the emission remains optically thick. These sources are indicated by pink circles with arrows, highlighting their positions within the parameter space.

The main result is that the sources in this sample lie well above the radio-jet relation. This strongly supports the interpretation that the compact radio emission detected here arises from HII regions rather than from ionised jets. Importantly, even the lower limits on the Lyman continuum fluxes for the HCHII region candidates remain well separated from the jet relation, indicating that these sources are also consistent

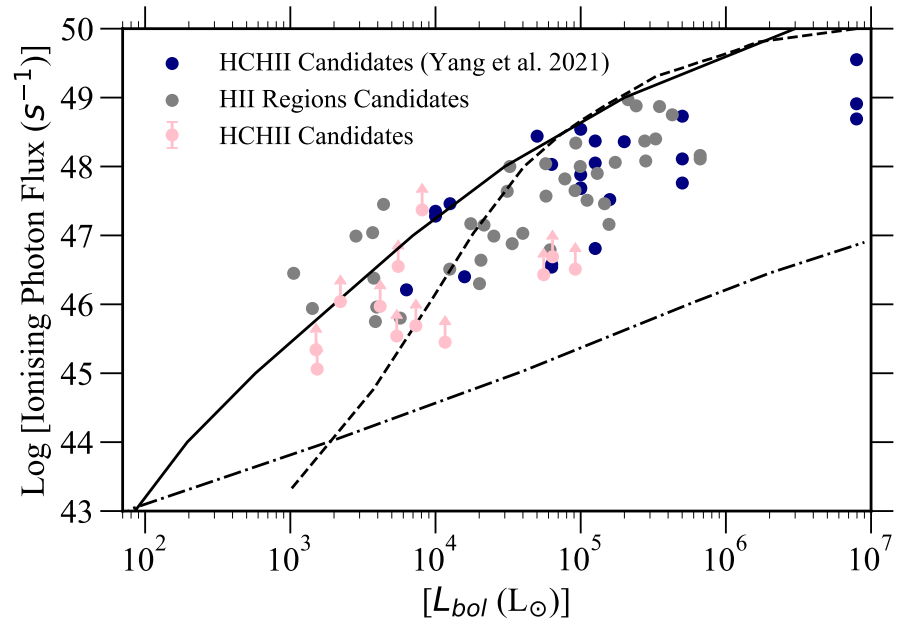


FIGURE 3.16: Lyman continuum photon flux as a function of bolometric luminosity for the HII region sample. The pink and grey circles show the HCHII region candidates and the remaining HII regions, respectively. The navy points show the HCHII regions identified in Yang et al. (2021). The dashed line indicates the expected relation for OB ZAMS stars (Davies et al., 2011; Martins et al., 2005), the dot-dashed line shows the fitted relation for radio jets from Purser et al. (2016) and Purser et al. (2021), and the solid line shows the Lyman continuum output expected from a blackbody with the same radius and temperature as a ZAMS star (Sánchez-Monge et al., 2013a).

with HII regions. This suggests that, despite their optically thick nature, these objects are unlikely to be dominated by jet emission and are instead strong candidates for HC HII regions. In this sense, the Lyman continuum comparison provides an important consistency check on the classifications derived from the positional associations, water maser incidence, and spectral index measurements presented in the preceding subsections.

The candidate sources are also compared with the distribution of the 24 known HC HII regions and candidates compiled by Yang et al. (2021), as shown in Figure 3.16. In this comparison, both samples occupy a similar region of parameter space in Lyman continuum photon flux and bolometric luminosity, indicating that the sources identified here are consistent with the known HC HII population in terms of their ionising properties. However, the objects presented in this work extend this distribution to bolometric luminosities approximately an order of magnitude lower than those previously reported. This suggests that the selection strategy adopted in this pilot study is capable of identifying HC HII regions associated with somewhat less massive high-mass stars than have typically been included in earlier samples, potentially probing an earlier phase of HC HII region evolution.

When considered together, the evidence presented in this section supports the interpretation that the majority of the retained sources are genuine compact HII regions. In particular, the strong correlation between Lyman continuum flux and bolometric luminosity, the clear separation from the radio-jet relation, and the consistency with the known HC HII region population all indicate that the observed radio emission is dominated by photoionised gas rather than accretion-driven jets.

Within this refined sample, the sources exhibiting positive or rising spectral indices remain the strongest candidates for HC HII regions, as these spectral properties are consistent with partially optically thick free-free emission. These objects therefore represent the most promising targets for follow-up observations, and form the basis for the discussion in the following section.

3.4 DISCUSSION

The results presented above reduce the original set of high-frequency radio detections to 13 strong HC HII region candidates (Section 3.3.2(e)). These sources are identified through a consistent combination of observational properties: compact 23.7 GHz radio emission, close positional association with methanol masers and dense dust clumps (Figure 3.10), and either a positive spectral index or a lower limit consistent with optically thick free-free emission between 5 and 23.7 GHz. The focus now shifts from their identification to what they reveal about the earliest stages of ionisation in massive star-forming regions.

The candidate sample does not represent a single sharply defined class of object, but instead spans a narrow and physically meaningful range of early ionised evolutionary stages. This is reflected in their distribution in Lyman continuum photon flux and bolometric luminosity (Figure 3.16), where the candidates occupy a region consistent with HC HII regions while extending to lower luminosities than previously identified samples.

At one end of this range are deeply embedded sources with no detectable 5 GHz counterpart, weak or absent mid-infrared emission, and positive lower limits to the spectral index. At the other are more developed objects that are already detectable at both 5 and 23.7 GHz, but still retain compact radio emission with rising spectral indices. This behaviour indicates that the selection method is sensitive not only to established compact HII regions, but also to the broader evolutionary interval over which ionisation first becomes detectable and begins to emerge from its natal environment.

This interpretation is supported by the distribution of ATLASGAL classifications across the candidate sample (Table 3.5; Figure 3.8). The candidates are not only found in clumps already classified as HII regions, but are also spread across protostellar, YSO, and HII region classes. This shows that the selection method is not just recovering previously known compact HII regions, but is also identifying sources that cover a short evolutionary sequence, including objects whose host clumps have not yet

TABLE 3.5: Summary of the physical properties of the ATLASGAL clumps hosting the compact and/or optically thick HII region candidates considered for follow-up observations.

Radio name	CSC name	Log (L_{bol}) ($L_{\odot}$)	Log (M_{fwhm}) ($M_{\odot}$)	$L_{\text{bol}}/M_{\text{fwhm}}$ ($L_{\odot}/M_{\odot}$)	ATLASGAL Classification
G004.680+0.277	AGAL004.681+00.277	3.35	1.95	25.2	HII region
G005.885−0.392	AGAL005.884−00.392	5.33	2.72	403	HII region
G012.112−0.127	AGAL012.111−00.126	3.18	2.24	8.58	YSO
G014.229−0.510	AGAL014.227−00.511	3.18	2.18	10.1	YSO
G018.735−0.227	AGAL018.734−00.226	4.81	3.79	10.3	HII region
G326.475+0.703	AGAL326.474+00.702	3.73	2.41	20.9	Protostellar
G331.442−0.187	AGAL331.442−00.187	3.91	2.64	18.5	YSO
G331.710+0.604	AGAL331.709+00.602	4.74	3.71	10.9	YSO
G332.826−0.549	AGAL332.826−00.549	5.54	3.09	283	HII region
G332.987−0.487	AGAL332.986−00.489	—	—	—	YSO
G336.983−0.183	AGAL336.984−00.184	4.24	2.06	154	HII region
G338.280+0.542	AGAL338.281+00.542	3.62	2.59	10.6	YSO
G338.566+0.110	AGAL338.567+00.109	3.74	2.72	10.5	Protostellar
G338.925+0.556	AGAL338.926+00.554	4.96	3.51	28.5	YSO
G339.622−0.121	AGAL339.623−00.122	3.87	2.28	38.2	YSO
G339.681−1.207	AGAL339.681−01.209	4.07	2.31	56.9	Protostellar

been identified as ionised. Overall, the sample traces the onset of ionisation at very early stages of massive star formation.

The clearest examples are the candidates associated with protostellar and YSO-classified clumps. These sources are compact, closely aligned with the methanol maser and the peak of the dust emission (Figure 3.4), and are often weak or not detected at mid-infrared wavelengths. In several cases, no 5 GHz counterpart is detected, even though sensitive survey data are available. In these situations, only lower limits on the spectral index can be measured, but these values are still positive and consistent with optically thick free-free emission. This is expected for very compact and dense ionised regions that are still deeply embedded within their natal clumps.

Several candidates show this behaviour clearly, including G326.475+0.703, G339.681-1.207, G332.987−0.487, G338.280+0.542, G338.925+0.556, and G339.622−0.121 (see Appendix 7.1.1). These objects are therefore the strongest candidates for very young, optically thick HC HII regions in the sample.

Other sources are less well constrained, but are still broadly consistent with the same interpretation. For example, G012.112−0.127 and G014.229−0.510 are compact and well embedded, but their spectral-index lower limits are not strongly positive. These sources are therefore less certain, but they still lie in the same general region

of parameter space. In these cases, the morphology and multi-wavelength associations support a young compact HII region interpretation, although higher-resolution observations are needed to confirm this. This uncertainty motivates the follow-up observations presented in the next chapter.

The candidates associated with clumps already classified as HII regions provide an important comparison. These sources show that the selection method is not limited to the most deeply embedded objects, but can also identify compact ionised components within more evolved regions. In these cases, extended ionised emission may already be present, but the high-frequency data reveal a compact component that is still optically thick.

This is consistent with the clustered nature of high-mass star formation, where multiple massive objects can form in the same clump and evolve at slightly different rates. In this picture, the compact high-frequency sources identified here are likely younger ionised regions embedded within more evolved and complex environments. G005.885–0.392 is a clear example: although it is already known as a bright and complex UC HII region, its radio spectrum between 5 and 23.7 GHz is still positive. G332.826–0.549 and G336.983–0.183 show similar behaviour. This suggests that the transition from hypercompact to ultracompact and compact HII regions is not sharp, but instead forms a continuous evolutionary sequence.

High-frequency radio observations therefore play an important role in identifying the earliest stages of ionisation. Lower-frequency surveys detect only some methanol maser sources, but the 23.7 GHz data reveal additional compact ionised emission that is either too weak or still optically thick at 5 GHz. As a result, high-frequency observations provide a more complete view of the onset of ionisation in massive star-forming regions.

These findings also have broader implications for our understanding of early high-mass star formation. The transition from a deeply embedded massive protostar to a detectable HII region is still not well understood, mainly because the youngest ionised regions are both very compact and optically thick at centimetre wavelengths. The identification of candidate HC HII regions at lower bolometric luminosities (Figure 3.16)

suggests that ionisation may become detectable earlier, and around less massive objects, than previously thought. This has important implications for the timescales over which ionisation develops, and for how feedback from massive stars begins to affect their surrounding environment. Overall, the results support a picture in which ionisation develops gradually over a range of evolutionary stages, rather than appearing suddenly at a single point.

The main outcome of this pilot study is the development of a consistent and physically motivated method for identifying candidate HC HII regions. The 13 sources identified here form a focused sample of compact ionised regions that appear to lie close to the onset of detectable radio emission from massive young stars. These sources provide a strong set of targets for higher-resolution follow-up observations, which are needed to resolve their structure and confirm their nature. These observations form the basis of the next chapter.

3.5 CONCLUSIONS

This chapter has used archival high-frequency radio continuum observations towards methanol maser sites to test whether these environments provide an effective way to identify the youngest and most compact HII regions. The results show that they do and that observations at 23.7 GHz recover a population of compact ionised sources that would be difficult to identify from lower-frequency radio data alone.

A total of 68 high-frequency radio detections were identified across 128 ATCA fields centred on 141 MMB methanol masers. Multi-wavelength comparison with methanol masers, ATLASGAL dust emission, existing 5 GHz radio catalogues, and infrared imaging shows that 49 of these sources are associated with HII regions. This confirms that the majority of the detected high-frequency radio emission is linked to massive star formation.

The refined sample was then examined using ATLASGAL classifications, positional agreement with other tracers, water maser associations, radio spectral indices,

and clump properties. This shows that the radio-selected HII regions are not confined to clumps already classified as HII regions, but are also found in protostellar and YSO-classified clumps. The sample therefore appears to trace a short but important interval in the evolution of massive star-forming regions, spanning the onset of detectable ionisation through to somewhat more developed compact HII regions.

Spectral index measurements and lower limits provide one of the clearest indicators of this behaviour. Of the 28 compact sources for which spectral index measurements or lower limits could be obtained, 13 show either positive spectral indices or lower limits consistent with optically thick free-free emission between 5 and 23.7 GHz. These sources are identified as the strongest HC HII region candidates in the sample.

The physical properties of the host clumps further support this interpretation. The radio-selected HII regions occupy a relatively well-defined region of parameter space, with bolometric luminosities above $10^3 L_{\odot}$ and luminosity-to-mass ratios above approximately $5.1 L_{\odot} M_{\odot}^{-1}$. In addition, comparison between Lyman continuum flux and bolometric luminosity shows that the compact radio sources lie well above the empirical radio-jet relation, supporting the interpretation that the detected emission arises predominantly from compact HII regions rather than ionised jets.

Overall, this pilot study demonstrates that combining high-frequency radio continuum observations with methanol maser selection provides a practical and effective way to identify young compact HII regions, including sources that are likely to remain optically thick at lower radio frequencies. The chapter establishes both the source-selection strategy and the observational framework for the higher-resolution follow-up presented in the following chapter, where the nature of these candidates is investigated in greater detail.

CHAPTER 4

SCOTCH II – THE HIGH RESOLUTION FOLLOW UP

This chapter is adapted from Patel et al. (2024), with a shortened introduction and observations section to minimise repetition. Unless otherwise stated, all work has been carried out by the author. Here, we present the high-resolution follow-up observations of a broader sample of compact and optically thick HII region candidates identified in Chapter 3.

4.1 INTRODUCTION

HC HII regions are of particular interest in the study of massive star formation because they are thought to represent a stage in which the ionised region is still confined to a very small spatial scale. This scale is likely consistent with a single high-mass star, or possibly a binary system, in contrast to UC or compact HII regions, which are more

often associated with clusters of massive stars (e.g. Kurtz 2000; Hoare et al. 2007). Theoretical models suggest that O-type stars may form through continued accretion via an HC HII region, beginning from an intermediate-mass B-type protostar (Keto, 2007), although this scenario has not yet been definitively confirmed. As a result, HC HII regions provide an important opportunity to investigate the earliest stages of massive star formation.

The distinction between HC HII and UC HII regions is not sharply defined, as the evolution between these stages is expected to be continuous (Garay & Lizano, 1999; Yang et al., 2019). However, the number of known HC HII regions remains small, and a larger, well-characterised sample is needed to better constrain the properties of this early phase. One difficulty is that the youngest HII regions can remain optically thick at commonly used radio frequencies, making their ionising fluxes and physical sizes difficult to constrain. In addition, low angular resolution observations can blend compact ionised emission with more extended radio structure, limiting the ability to distinguish HC HII regions from more evolved UC or compact HII regions.

A targeted search towards methanol maser sites, combined with high-frequency radio continuum observations, is therefore well suited to identifying young compact HII regions that may be missed or poorly characterised at lower frequencies. In Chapter 3, high-frequency (23.7 GHz) radio continuum observations towards 141 6.7 GHz Class II methanol maser sites from the Methanol Multibeam survey (MMB; Green et al. 2009) were analysed using archival ATCA data (Titmarsh et al., 2016). As discussed in Chapter 3, Class II methanol masers are exclusively associated with the early stages of high-mass star formation (Breen et al., 2013), and therefore provide a natural starting point for identifying young ionised sources. The relatively low angular resolution (~ 20 arcsec) observations resulted in the detection of 68 compact radio sources, of which 49 were identified as HII regions, including 13 with spectral properties consistent with optically thick emission between 5 and 23.7 GHz.

Building directly on these results, the present chapter focuses on a higher-resolution (~ 0.5 arcsec) study of a refined sample of 39 compact (i.e., y-factor ($f_{\text{int}}/f_{\text{peak}}$) < 2 ; see Chapter 3) and/or optically thick ($\alpha > 0.5$) HII regions identified in Chap-

ter 3. The improved angular resolution allows the true structure of these sources to be examined in greater detail. From this, physical properties are derived for each radio source, and the sample is classified into three groups: HC HII regions, UC HII regions, and transition objects that lie between these two evolutionary stages. The aim is to test whether the candidates identified at low angular resolution are genuinely compact ionised regions, and to determine where they lie within the HC HII–UC HII evolutionary sequence.

4.2 OBSERVATIONS AND DATA REDUCTION

4.2.1 OBSERVATIONAL SETUP

The observations presented in this chapter were obtained over four days in April 2022 towards 39 fields covering Galactic longitudes 2° – 18° and 326° – 340° . These fields were selected to observe radio sources that were either unresolved or optically thick at 23.7 GHz in the low-resolution (~ 20 arcsec) study presented in Chapter 3.

The observations were carried out with the ATCA in the 6A configuration, using all six antennas, with baselines ranging from 337 to 5939 m. As described in Section 2.3.2, the Compact Array Broadband Backend (CABB; Wilson et al. 2011) was configured with two 2 GHz continuum bands, each divided into 32 channels of 64 MHz, allowing simultaneous observations at 18 and 24 GHz. The ATCA primary beam has a full width at half maximum (FWHM) of 2.6 arcmin, and the synthesised beam in this configuration is ~ 0.4 arcsec at 24 GHz.

The targets were divided into four observing blocks based on sky position. Each field was typically observed in six 1.5-minute integrations spread over a range of hour angles to improve the uv -coverage, resulting in a total on-source integration time of approximately 10 minutes per field. This corresponds to a theoretical rms sensitivity of ~ 0.1 mJy beam $^{-1}$ at both frequencies, which is sufficient to detect an ionised nebula powered by a B0.5 star or an earlier type star, at a distance of 20 kpc (Giveon et al., 2005a; Urquhart et al., 2007).

TABLE 4.1: The CABB theoretical sensitivities for 18 GHz and 24 GHz, respectively. The synthesised beam is presented as beam major $\times$ beam minor. The noise values have been estimated assuming 10 minutes on-source integration time and stable weather conditions.

Target Group	Average Declination ($^{\circ}$)	Synthesised beam		Theoretical RMS	
		18 GHz (arcsec)	24 GHz (arcsec)	18 GHz (mJy beam $^{-1}$)	24 GHz (mJy beam $^{-1}$)
1	−52	0.61×0.48	0.46×0.36	0.094	0.160
2	−46	0.67×0.48	0.50×0.36	0.094	0.160
3	−25	1.14×0.48	0.86×0.36	0.098	0.166
4	−15	2.66×0.48	1.41×0.36	0.100	0.168

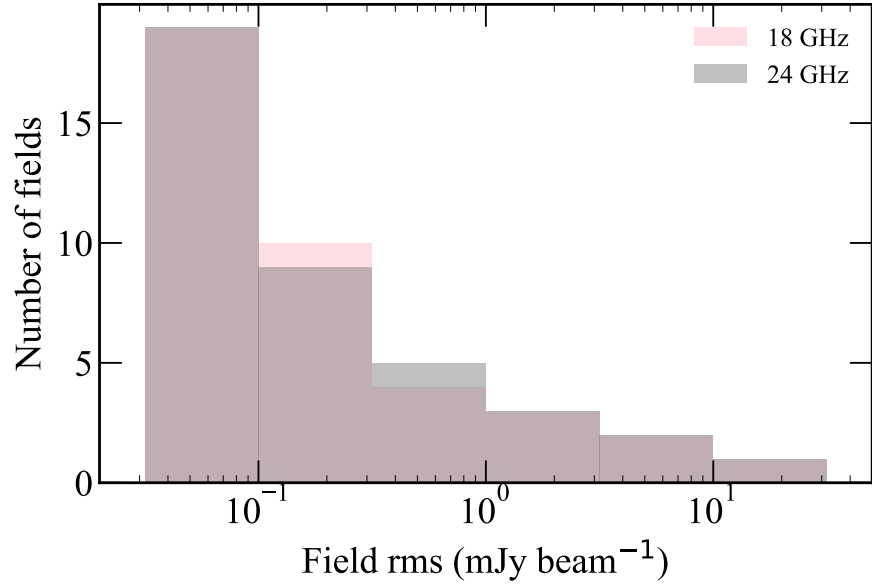


FIGURE 4.1: Histogram of the number of fields observed as a function of the map rms noise at both frequencies. The data have been binned using a value of 0.5 dex.

Most observations were carried out over a 10-hour period to provide relatively uniform uv -coverage. For higher-declination sources, corresponding to fields near the celestial equator ($\ell = 2^{\circ}$ – 18°), the available observing time was limited to approximately 5 hours. Because the ATCA is an east–west interferometer, this results in significantly elongated beams at higher declinations, with an average aspect ratio of approximately 5:1.

4.2.2 DATA REDUCTION AND IMAGING

The data were calibrated and imaged using the standard ATCA procedure described in Section 2.3.2 and applied in Chapter 3; only a brief summary is provided here. The 18 and 24 GHz datasets were imaged separately, and the final maps were produced by

Table 4.2: Observational parameters from all observed fields. The field names and pointing centres of the observations are based on the radio names and positions.

Field name	RA (J2000) (h:m:s)	Dec. (J2000) (d:m:s)	Field rms		Beam size 18 GHz			Beam size 24 GHz		
			18 GHz (mJy)	24 GHz (mJy)	Major (arcsec)	Minor (arcsec)	Position angle (°)	Major (arcsec)	Minor (arcsec)	Position angle (°)
G002.143+0.009	17:50:36.02	-27:05:46.9	0.1	0.1	1.8	0.5	-12.4	1.7	0.3	-11.1
G002.614+0.134	17:51:12.27	-26:37:38.8	0.2	0.2	1.9	0.5	-11.6	1.8	0.3	-10.4
G003.438-0.349	17:54:55.66	-26:09:47.4	0.1	0.2	2.0	0.5	-12.9	1.9	0.3	-11.2
G003.910+0.001	17:54:38.75	-25:34:44.7	0.5	0.4	2.1	0.5	-12.1	2.0	0.3	-10.5
G004.680+0.277	17:55:18.83	-24:46:29.5	0.1	0.1	2.2	0.5	-11.3	2.1	0.3	-10
G005.885-0.392	18:00:30.39	-24:04:00.1	15.9	16.6	2.2	0.5	-11.2	2.1	0.3	-9.9
G011.904-0.141	18:12:11.43	-18:41:29.4	0.3	0.3	3.8	0.4	-7.9	3.2	0.3	-7.3
G011.937-0.616	18:14:01.05	-18:53:24.9	1.1	1.9	3.8	0.4	-7.9	3.1	0.3	-7.4
G012.112-0.127	18:12:33.6	-18:30:06.8	0.1	0.1	4.0	0.4	-7.5	3.3	0.3	-7.0
G012.199-0.034	18:12:23.61	-18:22:54.7	0.2	0.2	4.2	0.4	-7.2	3.5	0.3	-6.8
G012.208-0.102	18:12:39.68	-18:24:20.9	0.5	0.5	4.2	0.4	-7.0	3.5	0.3	-6.6
G014.104+0.092	18:15:45.1	-16:38:51.3	0.1	0.1	8.6	0.3	-6.5	10.2	0.2	-6.4
G014.229-0.510	18:18:12.72	-16:49:26.7	0.1	0.1	5.1	0.4	-7.3	9.8	0.2	-6.2
G014.599+0.020	18:17:01.2	-16:14:39.1	0.1	0.1	7.7	0.4	-6.0	10.2	0.2	-5.7
G018.461-0.004	18:24:36.33	-12:51:04.2	2.0	1.4	7.6	0.4	-5.4	10.8	0.2	-4.9
G018.665+0.029	18:24:52.59	-12:39:19.3	0.1	0.1	8.0	0.4	-5.2	10.7	0.2	-4.7
G018.735-0.227	18:25:56.46	-12:42:48.8	0.1	0.1	7.7	0.4	-5.2	10.6	0.2	-4.6
G326.475+0.703	15:43:16.63	-54:07:15.0	0.1	0.0	0.9	0.5	-36.6	0.7	0.4	-27.2
G327.402+0.445	15:49:19.32	-53:45:14.4	0.3	0.4	0.9	0.5	-37.9	0.7	0.4	-26.9
G331.130-0.243	16:10:59.41	-51:50:23.5	0.3	0.2	0.9	0.5	-34.2	0.7	0.4	-23.6
G331.442-0.187	16:12:12.77	-51:35:11.0	0.2	0.1	0.9	0.5	-34.6	0.7	0.4	-23.5
G331.542-0.067	16:12:09.02	-51:25:47.5	1.5	1.0	0.9	0.5	-35.3	0.7	0.4	-26.1
G331.557-0.120	16:12:27.28	-51:27:32.4	0.2	0.2	0.9	0.5	-35.1	0.7	0.4	-25.6
G331.710+0.604	16:10:01.44	-50:49:28.9	0.0	0.0	0.9	0.5	-40.2	0.7	0.4	-28
G332.826-0.549	16:20:11.05	-50:53:14.2	6.8	7.0	0.9	0.5	-39.7	0.7	0.4	-28.5
G332.987-0.487	16:20:37.78	-50:43:49.7	0.1	0.1	0.9	0.5	-40.1	0.7	0.4	-28.1
G333.029-0.063	16:18:56.86	-50:23:54.2	0.1	0.2	0.9	0.5	-39.6	0.7	0.4	-28.3

Note: only a small portion of the data is provided here, the full table is available in Chapter 7.2 of the appendix.

combining the data from all four observing days to improve both the *uv*-coverage and the signal-to-noise ratio. The rms noise in each field was estimated from emission-free regions close to the centre of the image. The distribution of rms values is shown in Figure 4.1, with a median value of $\sim 0.13 \text{ mJy beam}^{-1}$, consistent with the theoretical sensitivity.

Due to the interferometric filtering, the largest well-imaged angular scales are 5.5 and 4.0 arcsec at 18 and 24 GHz, respectively. The observational parameters of the final maps are listed in Table 4.2. With the observational setup and imaging procedures established, the reduced maps can now be analysed to identify radio sources and construct the final catalogue.

4.2.3 SOURCE PARAMETERS AND FINAL CATALOGUE

This process follows the same general approach as in Chapter 3, but takes advantage of the improved angular resolution of these data.

Radio sources were identified relative to the local rms noise level measured for each field. The rms was estimated from emission-free regions close to the centre of each image, ensuring a representative measure of the background noise. A nominal detection threshold of 3σ was adopted, such that only emission exceeding three times the local noise level was considered a potential source.

To aid source identification, each map was examined using overlaid contour levels, starting at 3σ and increasing in steps of 2σ . Genuine sources typically appear as coherent, well-defined structures that persist across multiple contour levels and exhibit smooth, consistent morphologies. In contrast, noise features tend to appear as small, irregular structures that do not persist as the contour level increases. This approach allows both compact and extended emission to be identified, while providing a clear distinction between real sources and noise.

Contour maps were used as an initial guide to identify candidate detections; however, all sources were confirmed through visual inspection. Each field was examined by eye to verify that the emission represented genuine radio structure rather than imaging artefacts, such as sidelobes or large-scale patterns introduced by incomplete

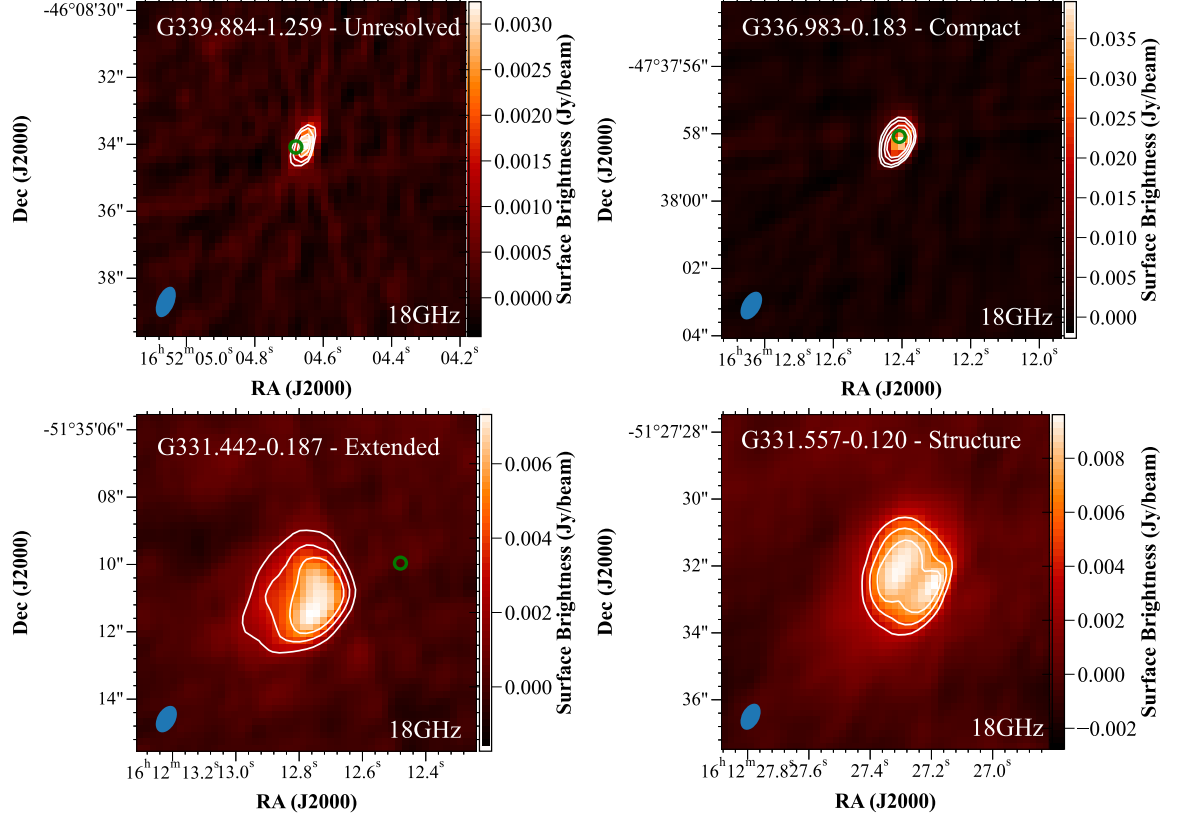


FIGURE 4.2: Examples of four radio sources with different morphologies. The top-left panel presents an unresolved radio source (G339.884–1.259), the top-right is compact radio source G336.983–0.183, the bottom-left panel shows an extended source (G331.442–0.187) and the bottom-right shows a structured source (G331.557–0.120). The white contours of each map start at a level of 3σ and are equally spaced by 3σ . The orange ellipse shows the resulting fit from IMFIT to the radio emission while the green circles show the position of the methanol maser(s) located in the field. The filled blue ellipse in the bottom left-hand corner of each image indicates the size and orientation of the synthesised beam.

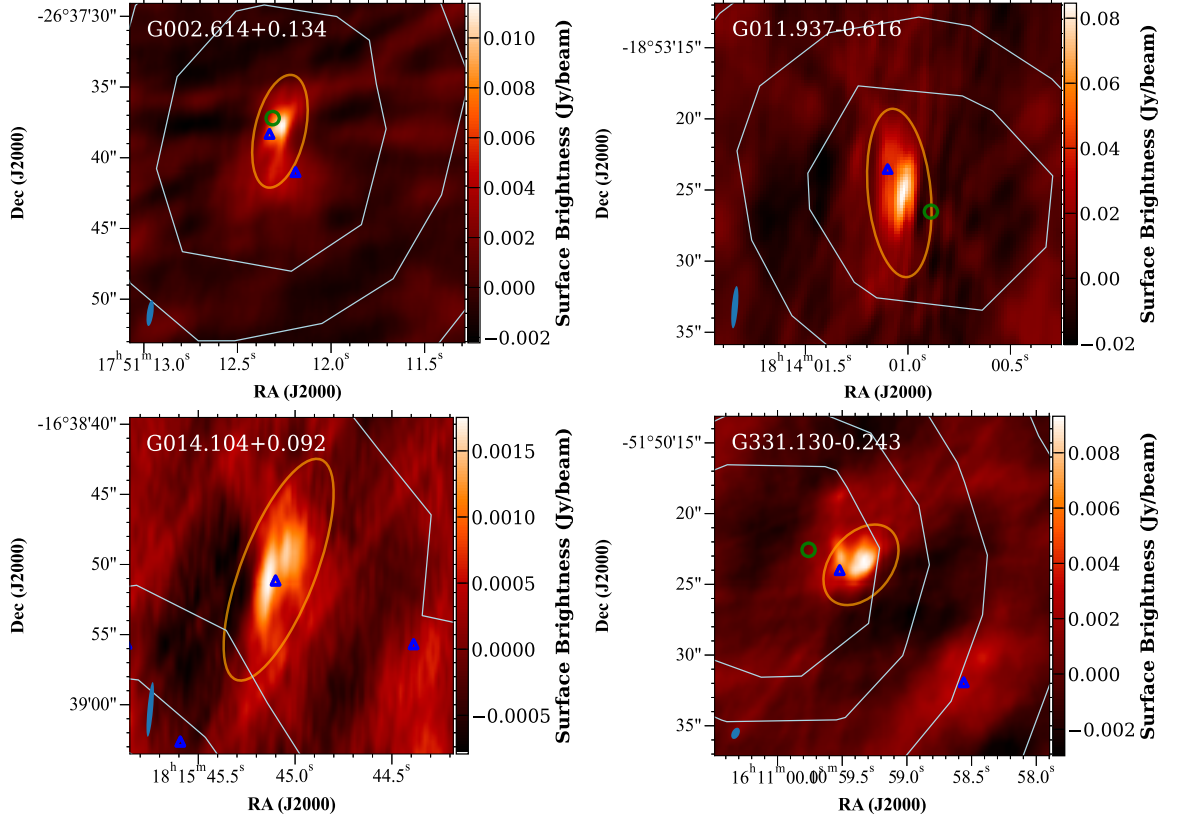


FIGURE 4.3: Examples of four radio fields excluded from the final sample. The orange ellipse shows the resultant fit to the radio emission while the green circles show the position of the methanol maser(s) located in the field. The blue triangles show the position of any low-frequency (5 GHz) radio counterparts. The grey contours trace the 870 m dust emission from ATLASGAL (Schuller et al. 2009). The filled blue ellipse in the bottom left-hand corner of each image indicates the size and orientation of the synthesised beam.

uv-coverage. During this process, particular care was taken in fields with higher noise levels or complex emission.

In some cases, multiple radio sources were identified within a single field. These were assessed individually, and where possible, distinct components were separated and characterised. In more complex regions, where emission components could not be reliably separated, the structure was treated as a single source.

Radio continuum emission above 3σ was detected in 35 of the 39 observed fields, corresponding to a recovery rate of approximately 90 per cent. Of these, 22 fields contain a single compact radio source, and 12 contain a single extended source. The remaining field contains two distinct radio sources.

Seven fields (G002.614+0.134, G011.937−0.616, G014.104+0.092, G331.130−0.243, G332.826−0.549, G333.163−0.100, and G340.056−0.244) show evidence of large-scale, over-resolved emission, with $f_{\text{int}24\text{ GHz}}/f_{\text{peak}23.7\text{ GHz}} > 2$. In each case, the integrated flux

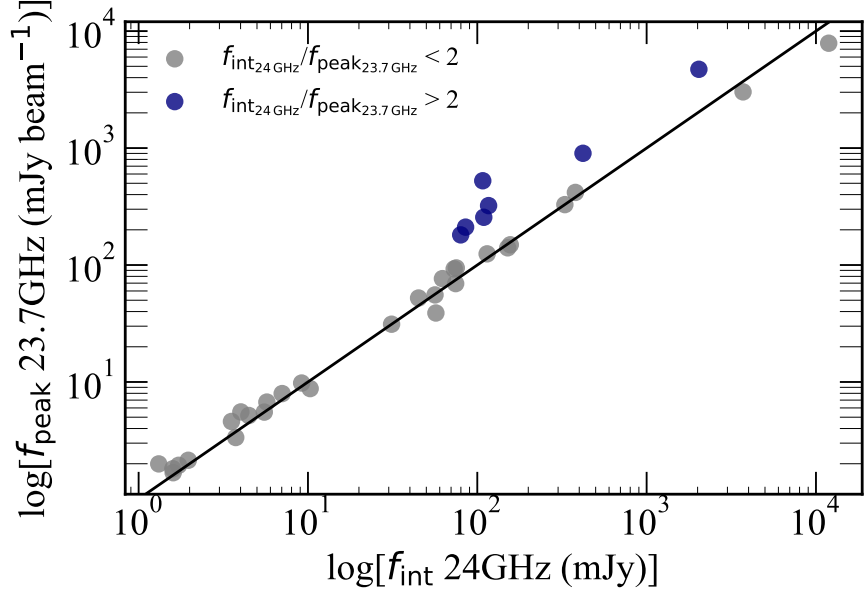


FIGURE 4.4: Distribution of the integrated flux density at 24 GHz from this study versus the peak flux densities at 23.7 GHz in Chapter 3 for the detected radio sources. Sources shown as blue circles are probably affected by spatial filtering. The solid black line represents the line of equality.

density measured at 18 and 24 GHz is lower than the 23.7 GHz peak flux density reported in Chapter 3, indicating that flux has been resolved out in the high-resolution data due to spatial filtering.

Figure 4.4 compares the integrated flux densities at 24 GHz from this chapter with the 23.7 GHz peak flux densities from Chapter 3. Most sources lie close to the line of equality, showing that there is no significant loss of flux for the majority of the sample. The outliers, shown in blue, correspond to the seven over-resolved fields listed above, which are therefore excluded from the final catalogue. Four examples of these excluded fields are shown in Figure 4.3. The close agreement in flux density for the compact sources suggests that there is little evidence for strong variability over the approximately 10-year interval between the low- and high-resolution observations.

As noted in Section 4.2.1, the synthesised beam is significantly elongated for the higher-declination fields. Five fields are affected by this. In these cases, the elongation is visible in the maps and limits the accuracy of the derived source sizes. One of these fields, G014.604+0.016, contains two radio sources for which the extracted fluxes are unlikely to be reliable, and both are therefore excluded from further analysis. Another

source, G018.735–0.227, shows the strongest elongation. Although it is reliably detected at 18 GHz ($\text{SNR} = 9.5$), the emission cannot be deconvolved at 24 GHz. For this source, the 18 GHz fit is used to estimate upper limits to the 24 GHz flux density. The remaining three fields are retained, with a note that their source sizes are less reliable.

Four fields (G012.112–0.127, G014.229–0.510, G331.710+0.604, and G338.280+0.542) are non-detections in the present data. These were weak detections at 23.7 GHz in Chapter 3, with $\text{SNR} < 3$ and average noise values of $\sim 0.5 \text{ mJy beam}^{-1}$. The higher-resolution data presented here are more sensitive, with typical noise levels of $\sim 0.08 \text{ mJy beam}^{-1}$. One possibility is therefore that the earlier detections were false positives caused by the higher noise in the Chapter 3 data. Alternatively, because the present observations are insensitive to structures larger than about 5 arcsec, the emission may have been resolved out by spatial filtering. A third possibility is that these are variable HII regions, as discussed by Yang et al. (2023).

The positions, peak and integrated flux densities, and source sizes of the remaining 27 compact radio detections were measured using the MIRIAD task IMFIT. As in Chapter 3, a polygon was drawn manually around each source to constrain the fit to the relevant emission and minimise contamination from nearby noise or unrelated structure.

4.3 RESULTS

This section presents the results of the high-resolution follow-up observations. We begin by describing the observed properties of the detected radio sources, including their morphology and flux characteristics. We then investigate their radio spectral energy distributions and derive the corresponding physical parameters. Finally, the sample is classified to distinguish between HC HII regions, UC HII regions, and transition objects.

Table 4.3: Extracted source parameters from our detected radio sources. Column 1 is the radio name, which is a combination of the Galactic longitudes and latitudes determined by fitting ellipsoidal Gaussian using IMFIT, Columns 2–7 present 18-GHz source parameters and columns 8–14 present 24-GHz source parameters. Sources with – are those for which sizes could not be deconvolved. Sources with a † indicate those with a poor synthesised beam.

Radio name (1)	18GHz						24GHz						
	f_{peak} (mJy beam ⁻¹) (2–3)	Δf_{peak} (mJy beam ⁻¹) (2–3)	f_{int} (mJy) (4–5)	Δf_{int} (mJy) (4–5)	$\theta_{\text{maj}} \times \theta_{\text{min}}$ (PA) (arcsec × arcsec (°)) (6–7)	$\theta_{\text{maj,d}} \times \theta_{\text{min,d}}$ (PA _d) (°) (6–7)	f_{peak} (mJy beam ⁻¹) (8–9)	Δf_{peak} (mJy beam ⁻¹) (8–9)	f_{int} (mJy) (10–11)	Δf_{int} (mJy) (10–11)	$\theta_{\text{maj}} \times \theta_{\text{min}}$ (PA) (arcsec × arcsec (°)) (12–13)	$\theta_{\text{maj,d}} \times \theta_{\text{min,d}}$ (PA _d) (°) (12–13)	θ_s (arcsec) (14)
G002.143+0.009†	2.3	0.17	4.2	0.56	2.3 x 0.6 (–8.4)	1.5 x 0.4 (–8.1)	1.8	0.36	3.5	1.1	2.3 x 0.5 (–7.5)	1.5 x 0.3 (–3.3)	0.70
G003.438–0.349†	9.1	0.58	89	13	4.1 x 2.1 (+0.1)	3.6 x 2.0 (+3.6)	5.2	0.36	75	13	4.2 x 1.9 (–0.9)	3.9 x 1.9 (+1.3)	2.70
G003.910+0.001†	37	3.4	76	10	3.7 x 0.6 (–11)	3.0 x 0.3 (–10)	33	3.0	73	9.6	3.4 x 0.4 (–9.7)	2.7 x 0.3 (–9.2)	0.87
G004.680+0.277†	6.5	0.64	9.8	1.4	3.3 x 0.5 (–9.8)	–	5.5	0.61	9.2	1.5	3.0 x 0.4 (–9.5)	2.2 x 0.2 (–9.1)	0.65
G005.885–0.392†	470	49	15000	9200	6.8 x 4.5 (+57)	6.8 x 4.1 (+60)	280	32	12000	5400	6.5 x 4.0 (+31)	6.4 x 3.8 (+35)	4.90
G011.904–0.141†	15	2.2	41	12	4.6 x 0.9 (–1.2)	3.5 x 0.7 (+1.5)	14	1.6	40	8.7	3.5 x 0.7 (–3.5)	2.4 x 0.6 (–1.9)	1.20
G012.199–0.034†	6.4	0.49	54	8.2	5.7 x 2.1 (–1.6)	4.7 x 2.0 (+0.1)	3.5	0.24	57	14	7.2 x 1.9 (+2.8)	6.6 x 1.9 (+4.2)	3.50
G012.208–0.102†	22	1.0	160	13	5.2 x 2.0 (–11)	4.1 x 1.9 (–16)	12	0.64	150	24	6.3 x 1.7 (–11)	5.7 x 1.7 (–12)	3.10
G018.461–0.004†	64	5.1	390	70	7.5 x 1.6 (–3.0)	5.9 x 1.6 (–2.1)	37	4.2	380	120	10 x 1.3 (+0.18)	9.3 x 1.2 (+1.3)	3.40
G018.665+0.029†	2.2	0.18	5.9	0.86	6.1 x 0.9 (–2.7)	3.7 x 0.8 (+0.1)	1.5	0.16	5.5	1.0	6.5 x 0.8 (–3.1)	4.3 x 0.7 (–1.8)	1.80
G018.735–0.227†	0.62	0.15	1.7	1.3	7.9 x 0.7 (–2.0)	6.2 x 0.5 (–0.6)	< 0.54	–	< 1.4	–	–	–	–
G326.475+0.703	0.75	0.053	0.84	0.19	0.8 x 0.6 (–33)	–	1.2	0.36	2.0	1.1	0.8 x 0.4 (–25)	0.7 x 0.1 (–24)	0.27
G327.402+0.445	41	1.6	120	6.9	1.6 x 0.9 (–17)	1.1 x 0.4 (–11)	30	2.3	110	13	1.4 x 0.7 (–13)	1.1 x 0.6 (–9.8)	0.80
G331.442–0.187	7.2	0.34	78	9.9	2.5 x 2.0 (–23)	2.0 x 1.1 (–21)	3.8	0.2	75	8.2	2.7 x 1.8 (–29)	2.1 x 1.3 (–30)	1.70
G331.542–0.067	130	5.1	320	18	1.3 x 0.9 (–37)	1.0 x 0.7 (–38)	80	4.1	330	25	1.3 x 0.8 (–25)	1.2 x 0.7 (–25)	0.91
G331.557–0.120	11	0.33	170	7.4	3.0 x 2.3 (–25)	1.7 x 1.3 (–24)	6.1	0.29	160	13	3.1 x 2.2 (–19)	1.8 x 1.4 (–18)	1.60
G332.987–0.487	6.4	0.78	9.2	1.7	1.1 x 0.6 (–15)	–	7.0	1.1	12	2.9	0.9 x 0.5 (–9.2)	0.7 x 0.2 (+3.6)	0.36
G333.029–0.063	15	1.6	25	3.7	1.2 x 0.6 (–22)	0.9 x 0.1 (–24)	10	2.7	27	4.2	1.2 x 0.5 (–23)	0.8 x 0.5 (–21)	1.10
G333.084–0.082	10	1.4	32	4.1	1.5 x 0.7 (–14)	1.1 x 0.6 (–10)	7.9	2.3	30	3.0	1.6 x 0.9 (–18)	1.1 x 0.6 (–15)	1.20
G334.087–0.160	21	2.6	63	7.5	3.2 x 2.1 (–11)	2.8 x 1.7 (–9.3)	14	1.6	60	8.0	3.1 x 1.8 (–7.8)	2.5 x 1.5 (–8.0)	2.20
G337.607–0.128	26	3.1	82	8.3	2.9 x 1.7 (–19)	2.3 x 1.4 (–17)	19	2.4	72	7.1	2.7 x 1.6 (–18)	2.3 x 1.5 (–17)	2.60
G338.825–0.107	23	3.7	65	6.1	2.7 x 1.6 (–17)	2.2 x 1.3 (–16)	17	2.1	60	7.5	2.6 x 1.4 (–15)	2.1 x 1.2 (–16)	2.30
G339.053–0.309	30	4.5	92	8.3	3.3 x 1.8 (–18)	2.7 x 1.5 (–17)	21	2.5	85	10	3.0 x 1.6 (–19)	2.5 x 1.4 (–19)	3.40
G340.275+0.225	21	2.9	81	7.4	2.9 x 1.8 (–18)	2.3 x 1.3 (–17)	18	2.1	72	7.2	2.7 x 1.6 (–16)	2.3 x 1.5 (–18)	2.10

4.3.1 OBSERVATIONAL RESULTS

With the final catalogue established in the previous section, we now examine the properties of the detected radio sources. The high-resolution catalogue is presented in Table 4.3, which lists the extracted parameters for the 27 compact radio sources detected at 18 and 24 GHz.

To characterise the nature of these detections, the sources are classified based on their observed morphology. Four morphological categories are identified: unresolved, compact, extended, and structured. Representative examples of each class are shown in Figure 4.2. The contour maps highlight variations in dynamic range, allowing a clear distinction between compact, bright emission and more diffuse structures with lower surface brightness.

Five sources are unresolved at 18 GHz, exhibiting y -factors close to unity, consistent with emission that is not spatially resolved by the synthesised beam. A further subset of sources are classified as compact, defined by y -factors < 2 and showing slight spatial extension without clear internal structure. Eleven sources are identified as extended, displaying larger-scale emission, while three sources exhibit complex sub-structure and are therefore classified as structured.

To quantify this classification, Figure 4.5 shows the relationship between integrated and peak flux density at both frequencies. The distribution closely follows the morphological classification described above, with sources clustering according to their y -factor. In total, 14 sources have y -factors ≤ 2 and are classified as compact, while the remaining 13 sources are extended. The strong agreement between visual morphology and flux-based diagnostics provides confidence that the sample can be robustly separated into compact and extended populations. Overall, the sample is approximately evenly divided between compact and extended sources, with a strong correspondence between the morphological classifications and the flux-based y -factor diagnostics. This agreement supports the robustness of the source classification and confirms that the high-resolution data are effectively resolving the structure of the compact ionised emission.

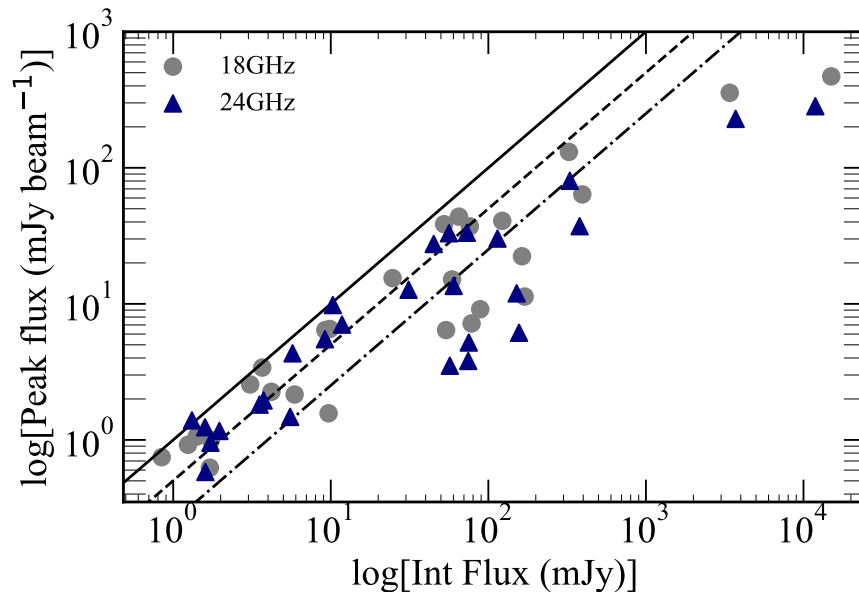


FIGURE 4.5: Distribution of the integrated flux density versus peak flux density for the 27 radio detections at 18 and 24 GHz. The solid line represents a line of equality where the flux densities are the same, indicating that the radio source is unresolved. The dashed line represents a line with $y = 2$ suggesting the radio source is compact. The dash-dotted line has a y -factor of 4; sources with y -factors above this are considered to be extended.

4.3.2 RADIO SPECTRAL ENERGY DISTRIBUTIONS AND DERIVED PHYSICAL PROPERTIES

The method used to derive the physical parameters of HII regions, including the SED modelling applied in this thesis, is described in Sections 2.1.2 and 2.1.3.

Having characterised the morphology of the radio sources, we now examine their physical properties using radio spectral energy distributions (SEDs). These provide estimates of source sizes, emission measures, and electron densities, which in turn allow us to calculate Lyman continuum fluxes and turnover frequencies. Estimating these properties from observations at a single frequency can lead to significant uncertainties. This arises for two main reasons: first, young HII regions may remain optically thick at the observing frequency, and second, the observed angular size can vary as a function of frequency (Yang et al., 2019). As a result, a multi-frequency approach is required to accurately characterise the physical properties of these sources.

To address this, we construct radio SEDs for all 27 HII regions using the available multi-wavelength data. In addition to the 18 and 24 GHz observations presented

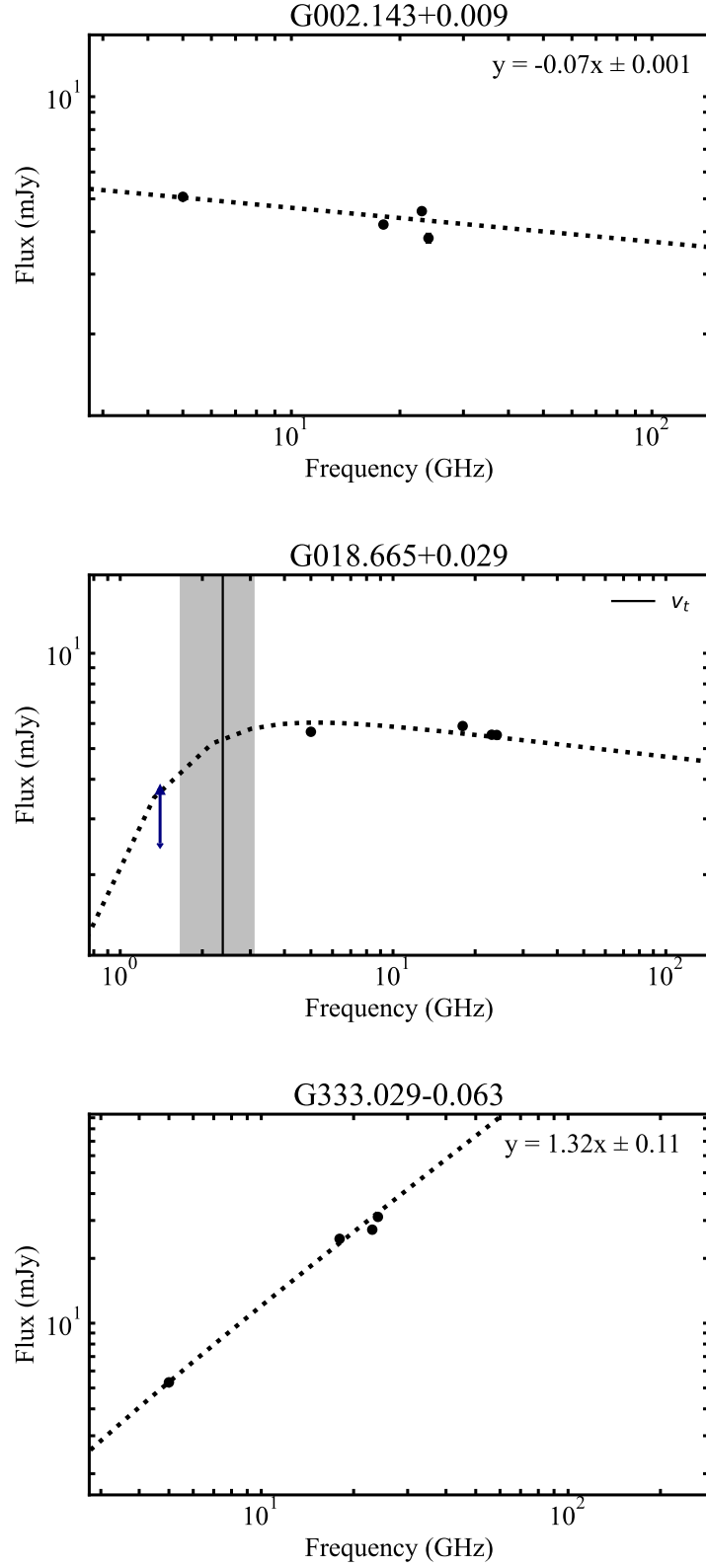


FIGURE 4.6: Three examples of radio SED fitting for varying optical depth. Top panel: SED fitting to the integrated flux density for an optically thin source (G002.143+0.009). Middle panel: SED fitting for radio source G018.665+0.029, an example of a source constrained by both optically thick and thin regimes (Yang et al., 2021). The vertical solid line represents the turnover frequency (ν_t) and the shaded region provides an estimation of the uncertainty. The blue triangle represents the 1.4-GHz peak flux density from THOR. Bottom panel: SED fitting to the integrated flux density for an optically thick source (G333.029−0.063).

here, we incorporate 5 GHz continuum data from the CORNISH-North (Purcell et al., 2013), CORNISH-South (Irabor et al., 2023), and MAGPIS (Becker et al., 1994) surveys. The corresponding 1σ sensitivities are 0.35, 0.11, and 0.179 mJy beam⁻¹, respectively. Where multiple 5 GHz measurements are available, the CORNISH-North and CORNISH-South data are prioritised due to their greater consistency within this study.

Of the 27 radio sources, 21 are associated with unresolved or compact 5 GHz counterparts (5 MAGPIS, 6 CORNISH-North, and 10 CORNISH-South). For the remaining six sources that are not detected at 5 GHz, we use the 3σ rms noise level of the corresponding maps to determine upper limits to the flux density.

To derive these properties, the SEDs are modelled using the standard homogeneous HII region model described in Section 2.1.3. Here, we briefly summarise the key aspects relevant to this analysis. In this model, each source is described by two free parameters: the electron density (n_e) and the physical diameter (diam). These parameters are constrained by fitting the observed radio continuum emission across the available frequency range. The uncertainties in the integrated flux densities, obtained from IMFIT (Table 4.3), are incorporated into the fitting process to provide reliable estimates of these parameters.

Once the electron density and diameter are determined, the emission measure is calculated using $EM = n_e^2 \times \text{diam}$ (Yang et al., 2021). The model assumes a simple spherical geometry and therefore provides averaged estimates of the physical properties of the ionised gas. These estimates are most reliable for sources that are optically thin across the frequency range considered (5–24 GHz). This multi-frequency approach is therefore essential for accurately constraining the physical properties of young HII regions, particularly for compact sources where optical depth effects and frequency-dependent structure can otherwise lead to significant uncertainties.

Examples of the resulting SED fits are shown in Figure 4.6, illustrating sources with optically thin, partially optically thick, and fully optically thick emission. The complete set of SEDs for all 27 sources is provided in Fig. 7.2 in Appendix 7.2.

In several cases, the available data do not fully constrain both the optically thick and optically thin regimes. Eleven sources lack sufficient frequency coverage to define

Table 4.4: Derived physical parameters for 26 HII regions. The sources whose properties were not extracted via the SED fitting are denoted by a †.

Radio name	Diameter (pc)	n_e (10^4 cm^{-3})	EM (10^7 pc cm^{-6})	$\log_{10} [N_{\text{Ly}}]$ (photons s^{-1})	ν_t GHz	Spectral type	Classification
G003.438−0.349	0.2649	0.61	0.66	48.62	—	O7	UCHII
G003.910+0.001†	0.0105	9.92	10.37	46.89	5.33	B0.5	HCII
G004.680+0.277	0.0030	22.97	15.98	45.98	6.55	B1	HCII
G005.885−0.392	0.0577	8.93	46.03	49.12	10.84	O6	UCHII
G011.904−0.141	0.0134	10.86	5.19	45.67	3.84	B1	HCII
G012.199−0.034†	0.1749	0.51	0.29	47.90	2.48	O9.5	UCHII
G012.208−0.102†	0.1883	0.92	1.05	48.52	2.19	O7.5	UCHII
G018.461−0.004	0.1903	1.12	2.39	48.82	2.34	O6.5	UCHII
G018.665+0.029†	0.0321	1.72	0.95	46.84	2.38	B0.5	HCII− UCHII
G018.735−0.227	0.0046	21.77	21.90	46.49	7.61	B0.5	HCII
G326.475+0.703†	0.0032	7.16	1.82	45.53	—	B1	HCII
G327.402+0.445	0.0258	5.42	7.59	47.51	4.60	B0	HCII− UCHII
G331.442−0.187	0.0246	4.68	5.40	47.38	3.91	B0	HCII− UCHII
G331.542−0.067	0.0308	7.29	16.40	48.03	6.64	O6.5	HCII− UCHII
G331.557−0.120	0.0525	3.27	5.61	48.01	3.98	O9.5	UCHII
G332.987−0.487	0.0014	118.90	195.35	46.25	—	B0.5	HCII
G333.029−0.063	0.0026	50.94	68.60	46.47	—	B0.5	HCII
G333.135−0.432	0.0486	7.81	29.63	48.70	8.79	O7	HCII− UCHII
G336.983−0.183	0.0099	14.98	22.16	47.17	7.66	B0.5	HCII
G338.566+0.110	0.0048	19.93	18.87	46.48	7.09	B0.5	HCII
G338.925+0.556	0.0008	109.97	95.42	46.54	15.34	B0.5	HCII
G339.282+0.136	0.0025	29.29	21.27	45.99	8.51	B1	HCII
G339.622−0.121	0.0007	88.01	54.26	45.17	11.73	B1	HCII
G339.681−1.207	0.0008	53.11	21.30	45.93	7.51	B1	HCII
G339.884−1.259†	0.0025	17.91	5.31	45.58	—	B1	HCII/Jet candidate
G339.980−0.539	0.0425	4.90	10.21	48.09	5.30	O9	HCII− UCHII

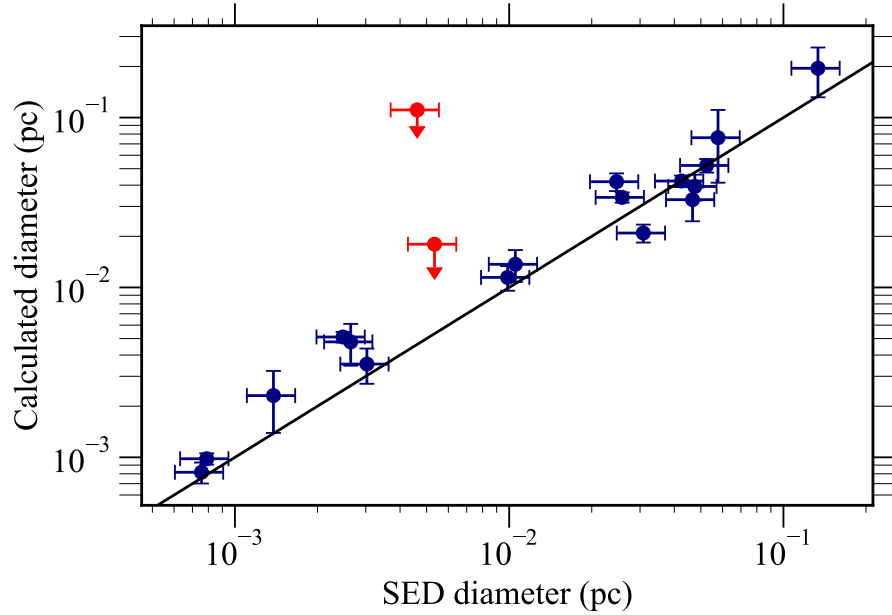


FIGURE 4.7: Distribution of the calculated sizes as a function of the SED derived sizes for the optically thin HII regions in this work. The red upper limits correspond to the two most elongated radio sources in our sample. The black solid line represents the line of equality.

the full SED shape. For five of these, located between $\ell = 12^\circ$ and 18° , additional constraints are obtained using 1.4 GHz data from the THOR (Wang et al., 2018) and MAGPIS (White et al., 2005) surveys. These measurements are treated as upper limits due to their lower angular resolution (~ 20 arcsec), but provide useful constraints on the low-frequency behaviour and allow the turnover frequency to be estimated.

For the remaining six sources without adequate constraints across the full frequency range, the SEDs are approximated using a linear fit, and source sizes are taken directly from the IMFIT measurements. In these cases, the physical parameters are derived using the equations presented in Section 2.1.2. Among these sources, two are consistent with optically thin emission between 5 and 24 GHz, while four remain optically thick at 24 GHz. For these optically thick sources, the derived parameters are likely to be biased, and are therefore presented as upper limits to the source size and lower limits to the electron density (n_e), emission measure, and Lyman continuum flux (N_{Ly}).

TABLE 4.5: Mean values of the physical parameters for HC HII regions, UC HII regions and transition objects identified in this work.

Parameters	# of objects	Size (pc)	n_e (cm^{-3})	EM (pc cm^{-6})	ν_t (GHz)
HC HII region	14	0.007	$10^{5.9}$	$10^{8.7}$	10.4
Transition objects	6	0.03	$10^{5.3}$	10^8	7.9
UC HII region	6	0.15	$10^{4.2}$	$10^{7.9}$	6.2

4.3.3 DERIVED PHYSICAL PROPERTIES

The SED fitting described above provides estimates of the source diameter, electron density, emission measure, Lyman continuum photon flux, and turnover frequency. Reliable kinematic distances are available for 26 of the 27 compact radio sources, so the physical analysis is restricted to these objects. The fitted SED parameters and derived physical properties are listed in Table 4.4.

As a consistency check, the physical parameters derived from the SED fitting were compared with those calculated using the standard equations introduced in Section 2.1.2, based on the formulations of Mezger & Henderson (1967) and Rubin (1968). This comparison is shown in Figure 4.7 for the optically thin sources. Most sources lie close to the line of equality, indicating good agreement between the two approaches. The two main outliers correspond to the most elongated radio sources in the sample, for which the measured diameters are treated as upper limits. To test this more quantitatively, a chi-squared test was performed to compare the SED-derived parameters with those calculated directly from the radio measurements. Excluding the two elongated sources, the diameter, emission measure, and electron density are consistent within their uncertainties, with p -values greater than 0.7. This agreement supports the reliability of the SED-derived parameters for the compact sources in the sample.

For one source, AGAL002.142+00.009, no reliable kinematic distance is available because of its close location to the Galactic centre. As a result, reliable values for the physical diameter and emission measure cannot be derived for this source.

The distributions of diameter, electron density, and emission measure are shown in Figure 4.8. The four sources that remain optically thick at 24 GHz are shown as upper limits in diameter and lower limits in electron density and emission measure.

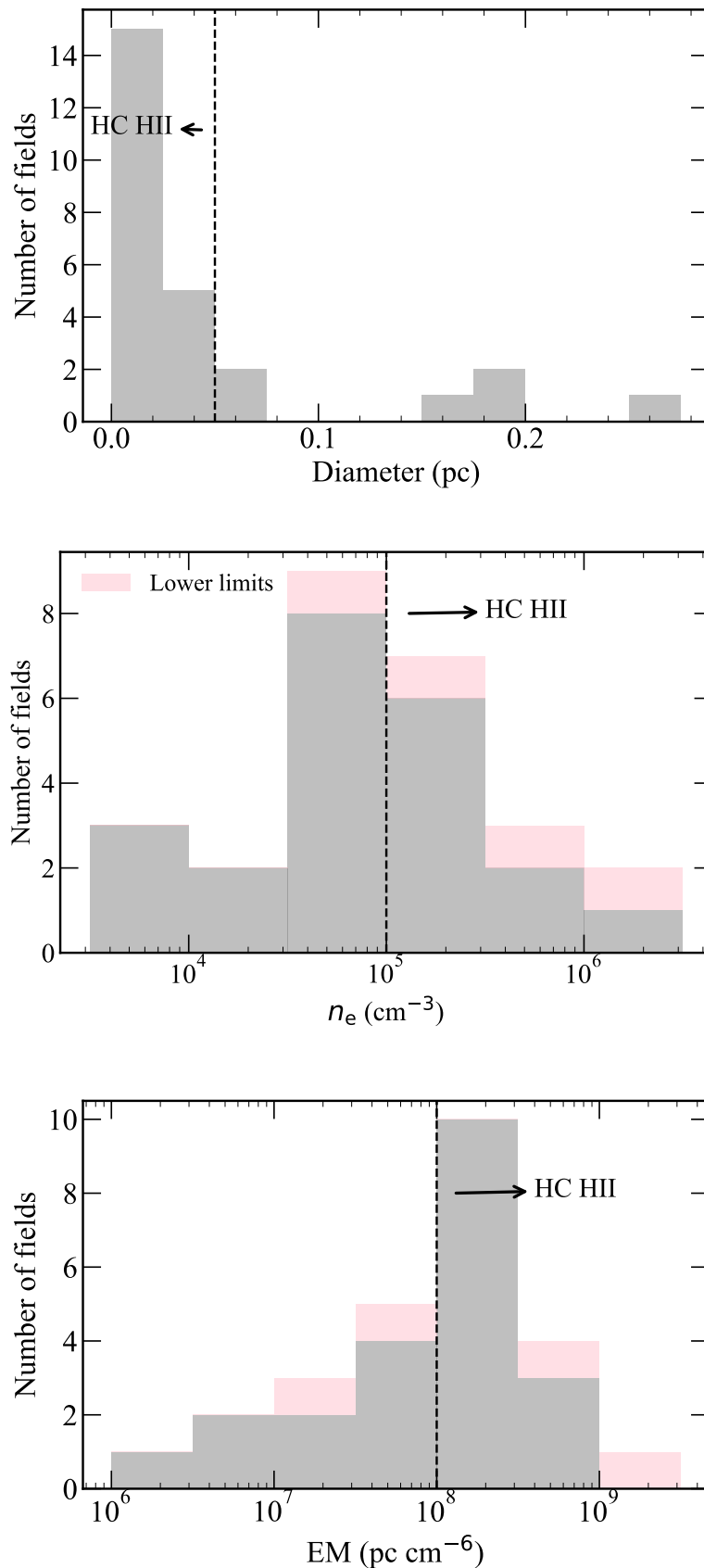


FIGURE 4.8: Histograms presenting the diameter (top panel), electron density (n_e ; middle panel) emission measure (bottom panel) and of the derived physical parameters. The bin sizes are 0.025 pc, 0.5 dex and 0.5 dex for diameter and n_e and emission measure, respectively. The pink fraction of the distribution represents values that are lower limits. The black arrows emphasise the region of parameter space in which we expect to find HC HII regions.

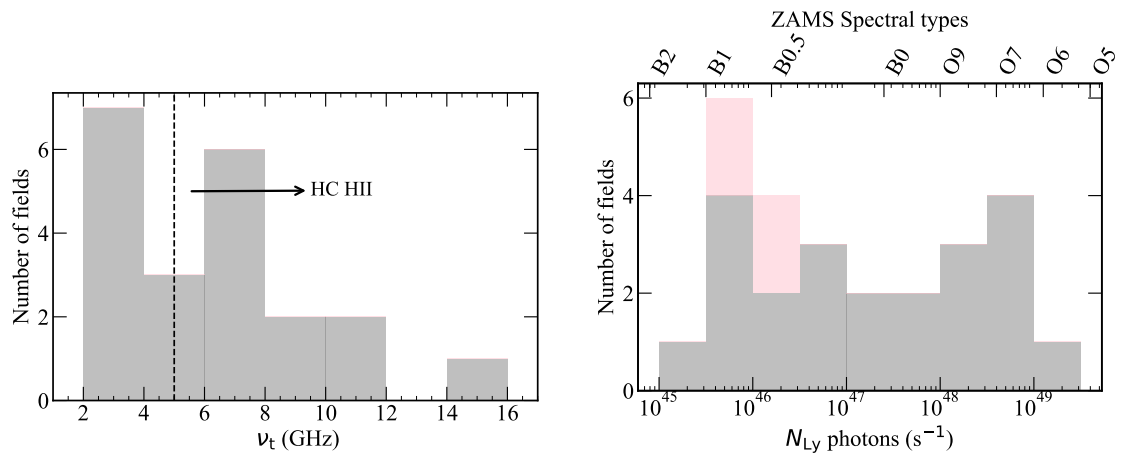


FIGURE 4.9: Histograms presenting the turnover frequency (ν_t) and N_{Ly} flux of the derived physical parameters for the 26 HII regions. The bin sizes are 2 GHz and 0.5 dex for ν_t and N_{Ly} , respectively. The pink fraction of the distribution represents values that are lower limits. The black arrow in the left panel emphasises the region of parameter space in which we expect to find HC HII regions.

The distributions show that many of the sources occupy the region of parameter space expected for HC HII regions, with small diameters, high electron densities, and high emission measures. The mean values for the HC HII regions, UC HII regions, and transition objects are summarised in Table 4.5.

The turnover frequency provides an additional measure of the optical depth of the ionised gas. As discussed in Chapter 2, the turnover frequency is the frequency at which the optical depth reaches $\tau_\nu = 1$, marking the transition from optically thick to optically thin free-free emission (Kurtz & Hofner, 2005). The turnover frequencies were calculated using Eq. 2.40. Following Yang et al. (2021), adopting typical uncertainties of 20 per cent in both diameter and emission measure gives an uncertainty of approximately 30 per cent in ν_t .

The distribution of turnover frequencies is shown in the left panel of Figure 4.9. For the sources whose physical parameters were obtained from SED fitting, the distribution peaks at ~ 8 GHz and has a mean value of ~ 9 GHz. This is higher than the typical turnover frequency of ~ 5 GHz expected for UC HII regions (Kurtz & Hofner, 2005), supporting the interpretation that a significant fraction of the sample contains very compact, dense ionised regions.

The Lyman continuum photon flux, N_{Ly} , was calculated using the integrated flux density and kinematic distance, following Eq. 2.39. The resulting distribution

TABLE 4.6: Quantitative criteria for the physical parameters for HC HII regions, transition objects between the two stages and UC HII regions from the literature.

Parameters	Size (pc)	n_e (cm^{-3})	EM (pc cm^{-6})
HC HII region	< 0.05	$> 10^5$	$> 10^8$
Transition objects	$0.05 - 0.1$	$10^4 - 10^5$	$10^7 - 10^8$
UC HII region	> 0.1	$< 10^4$	$< 10^7$

is shown in the right panel of Figure 4.9. The derived values range from $10^{44.8}$ to $10^{49.2}$ photons s^{-1} . If the ionising source is assumed to be a single zero-age main-sequence star, these values correspond approximately to spectral types between B2 and O5 (Panagia, 1973). The typical uncertainty in N_{Ly} is ~ 20 per cent, based on the uncertainties in distance and flux density (e.g. Urquhart et al., 2013; Sánchez-Monge et al., 2013b). For optically thick sources, the observed radio flux may underestimate the true ionising photon output, so these values are treated as lower limits. Taken together, these results show that a significant fraction of the sample occupies the region of parameter space expected for HC HII regions, characterised by small diameters, high electron densities, and high emission measures. The elevated turnover frequencies further support the presence of dense, compact ionised gas, while the range of derived properties indicates that the sample spans multiple evolutionary stages.

4.3.4 CLASSIFICATION OF THE COMPACT HII REGIONS

The final step is to use the derived physical properties to classify the compact radio sources. The criteria adopted for HC HII regions, UC HII regions, and transition objects are summarised in Table 4.6, based on values commonly used in the literature (e.g. Wood & Churchwell, 1989b; Kurtz et al., 1994; Gaume et al., 1995; Kurtz & Hofner, 2005; Hoare et al., 2007; Yang et al., 2021). Figure 4.10 shows the distribution of electron density, diameter, and emission measure for the 26 sources with reliable distances. The region expected for HC HII regions is indicated by the cuts $n_e > 10^5 \text{ cm}^{-3}$ and $\text{diam} < 0.05 \text{ pc}$. Sources that remain optically thick are shown with arrows, since their electron densities and emission measures are lower limits.

Using these criteria, 14 sources satisfy the physical conditions expected for HC HII regions, including the four optically thick sources. One of these sources,

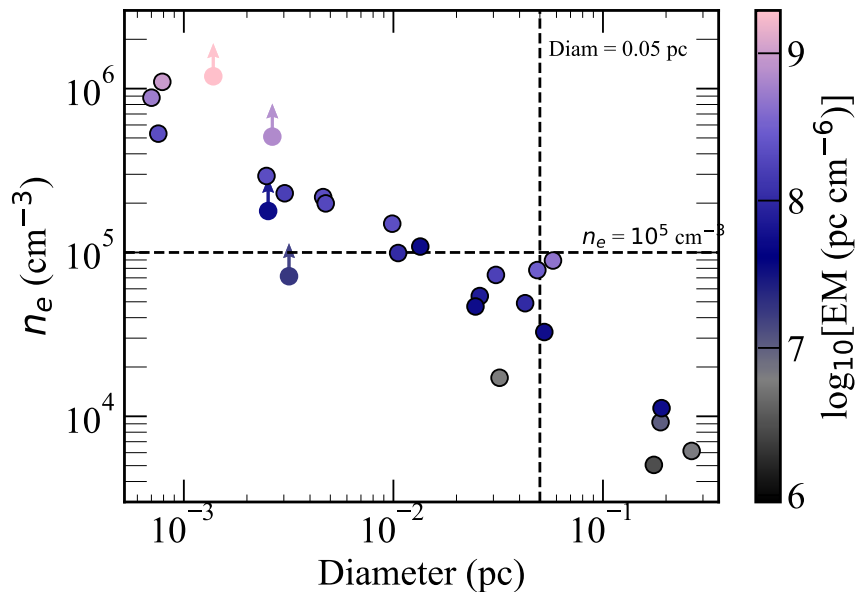


FIGURE 4.10: Distribution of the physical properties of the 26 radio sources identified in this work. The colour of the data points represents the emission measure of the radio source. Filled circles with upward-pointing arrows denote lower limits for n_e and emission measure, indicating optically thick radio sources. Vertical and horizontal dotted lines indicate the HC HII region cut-off.

G339.884–1.259, shows additional evidence for possible jet-like emission and is therefore discussed separately in Section 4.4.2. A further six sources satisfy the size criterion for HC HII regions but have lower electron densities, and are therefore classified as transition objects between the HC HII and UC HII stages. The remaining six sources are larger and less dense, and are classified as UC HII regions, comprising approximately 20 per cent of the classified sample. The large fraction of sources classified as HC HII regions demonstrates that the selection criteria adopted in Chapter 3 are highly effective at identifying very young, compact ionised regions. This confirms that methanol maser-selected samples, combined with high-frequency radio observations, provide a powerful method for probing the earliest stages of HII region evolution.

Overall, the high-resolution follow-up confirms that a substantial fraction of the compact radio sources selected in Chapter 3 are consistent with HC HII regions. The presence of transition and UC HII regions within the sample further suggests that these observations trace a range of evolutionary stages, providing a useful framework for investigating the development of compact HII regions.

4.4 DISCUSSION

The results presented in this chapter demonstrate that the high-resolution follow-up not only confirms the presence of HC HII regions within the sample, but also extends the known population towards sources associated with lower ionising luminosities. In particular, several of the identified HC HII regions appear to be ionised by early B-type stars, rather than being dominated solely by the more luminous O-type stars that characterise many previously studied samples. This suggests that the combination of methanol maser selection, high-frequency radio observations, and sub-arcsecond resolution provides a more sensitive probe of the earliest stages of HII region evolution across a wider range of stellar masses.

In this section, we first place the derived physical properties in the context of known HC HII and UC HII regions from the literature, before focusing on the optically thick HC HII regions, which are likely to represent the youngest objects in the sample, and examining their environments in more detail.

4.4.1 COMPARISON WITH KNOWN COMPACT HII REGION POPULATIONS

The analysis presented in Section 4.3.3 identifies 14 HC HII regions, 6 transition objects, and 6 UC HII regions. All of these sources are embedded within dense molecular clumps traced by ATLASGAL and are associated with either methanol maser emission or 5 GHz radio continuum emission, both of which are signposts of high-mass star formation. The derived Lyman-continuum fluxes indicate that these regions are ionised by ZAMS-stars spanning early B- to late O-type spectral classes.

To place these results in context, Figure 4.11 compares the diameter and electron density of the sources in this work with known HC HII and UC HII regions from the literature. The sources identified here occupy a similar region of parameter space to previously known compact HII regions, supporting their classification as young ionised

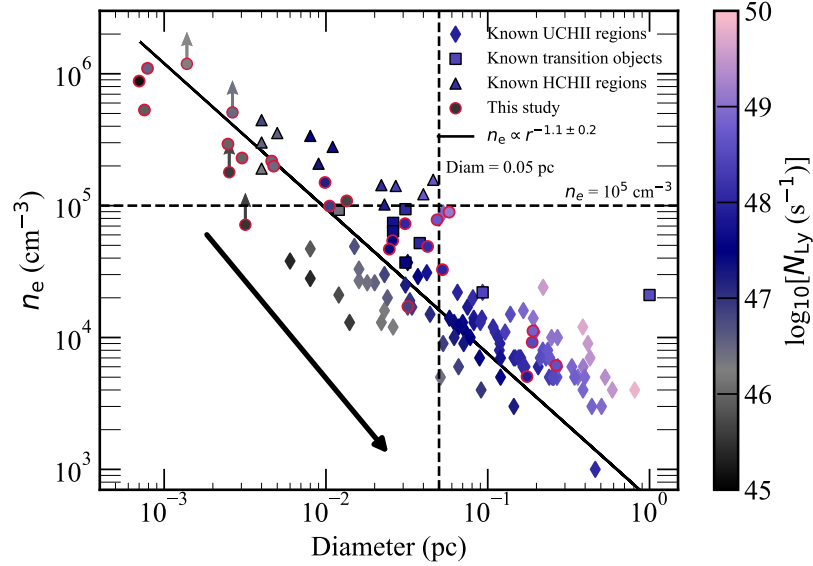


FIGURE 4.11: Distribution of the physical properties of the 26 radio sources identified in this work, plus HC HII and UC HII regions identified in Kalcheva et al. (2018); Yang et al. (2019); Yang et al. (2021). The colour of the data points denotes Lyman-continuum output (N_{Ly}). Diamonds show known UC HII regions while, triangles represent known HC HII regions. The filled circles represent the radio sources from this study where we use limits to show the optically thick radio sources. The black solid arrow shows the typical evolutionary trend a HC HII region is likely to follow as these objects expand while the solid black line represents the fitted evolutionary trend of expanding HII regions.

regions. However, they also extend the known population towards smaller sizes, higher densities, and lower ionising fluxes, particularly for the HC HII region candidates associated with early B-type stars.

The expected evolutionary behaviour for an expanding HII region can be described by a simplified Strömgren sphere model, in which the ionised region expands into the surrounding medium while the ionising photon flux remains approximately constant (Mezger & Henderson, 1967; Dyson & Williams, 1997). Under the assumption of a uniform density medium, this gives the relationship $n_e \propto r^{-1.5}$, where r is the radius of the ionised region. In practice, HII regions are unlikely to expand into a uniform medium, since massive star-forming regions are highly structured and contain strong density gradients. This is reflected in Figure 4.11, where the combined sample is better described by a shallower relationship, $n_e \propto r^{-1.1 \pm 0.2}$. This suggests that the expansion of compact HII regions is influenced by the inhomogeneous structure of the surrounding molecular gas.

To examine these trends in more detail, Figure 4.12 shows the Lyman-continuum

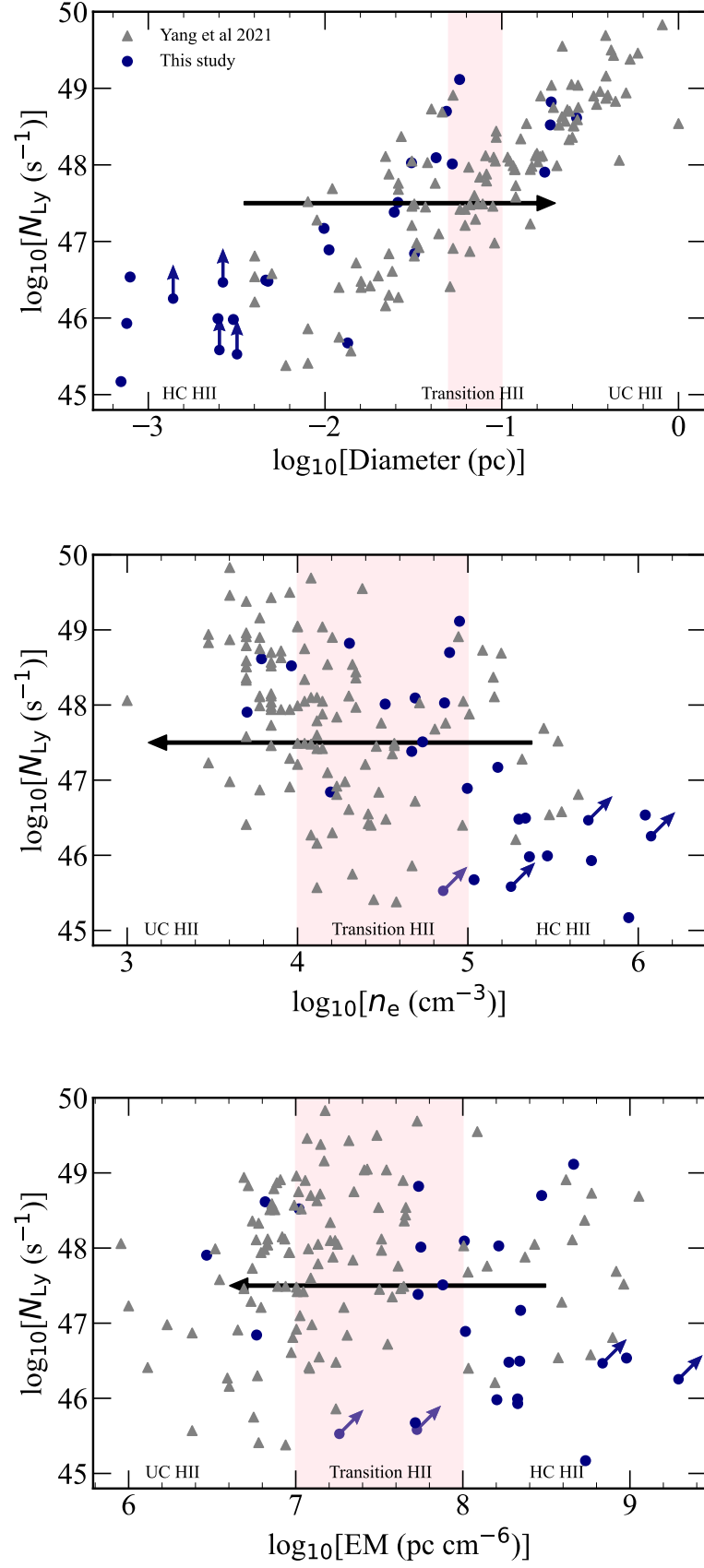


FIGURE 4.12: Evolutionary behaviour of the derived physical properties for the HII region sample. The top, middle, and bottom panels show the trends in physical diameter, electron density, and emission measure, respectively. The schematic evolutionary sequence of HII regions is indicated along the bottom of the figure, with the transition HII region phase marked by the shaded pink region.

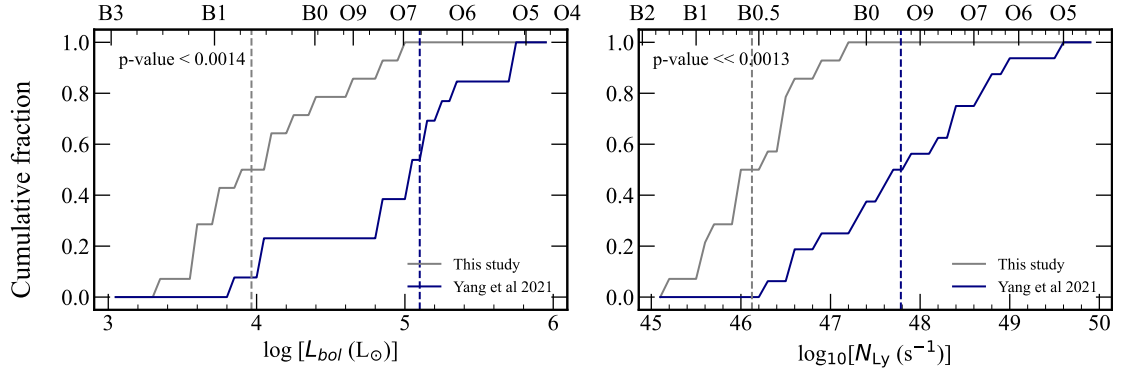


FIGURE 4.13: Cumulative distribution functions for bolometric luminosity (left panel) and N_{Ly} flux (right panel) for the sample of HCHII regions identified in this work and in the literature (Yang et al., 2021). The dotted line represents the median value of each sample.

flux as a function of diameter, electron density, and emission measure for the sources in this work and the literature comparison sample. The optically thick sources are shown as limits. The upper and middle panels show a strong positive correlation between diameter and N_{Ly} ($\rho = 0.85$, $p \ll 0.001$), and a moderate negative correlation between electron density and N_{Ly} ($\rho = -0.50$, $p \ll 0.001$). These trends indicate that the smallest and densest HII regions are typically associated with lower ionising fluxes, consistent with early B-type stars. In contrast, larger HCHII regions tend to be associated with higher ionising fluxes, characteristic of late O-type stars. This may reflect more rapid expansion around higher-luminosity stars, where stronger ionising fluxes drive the ionisation front to larger radii over a shorter timescale.

There is also a region of parameter space in which UCHII regions associated with early B-type stars are largely absent. This may be partly due to observational selection effects. As lower-luminosity HII regions expand, their surface brightness decreases, making them harder to detect. In addition, interferometric observations can filter out large-scale low-surface-brightness emission. These effects may make evolved, lower-luminosity UCHII regions more difficult to recover than compact, high-surface-brightness HCHII regions.

In the lower panel of Figure 4.12, no significant correlation is found between N_{Ly} and emission measure ($\rho = 0.002$, $p = 0.98$). This suggests that the emission measure remains largely independent of the ionising flux, consistent with the findings of Yang et al. (2021).

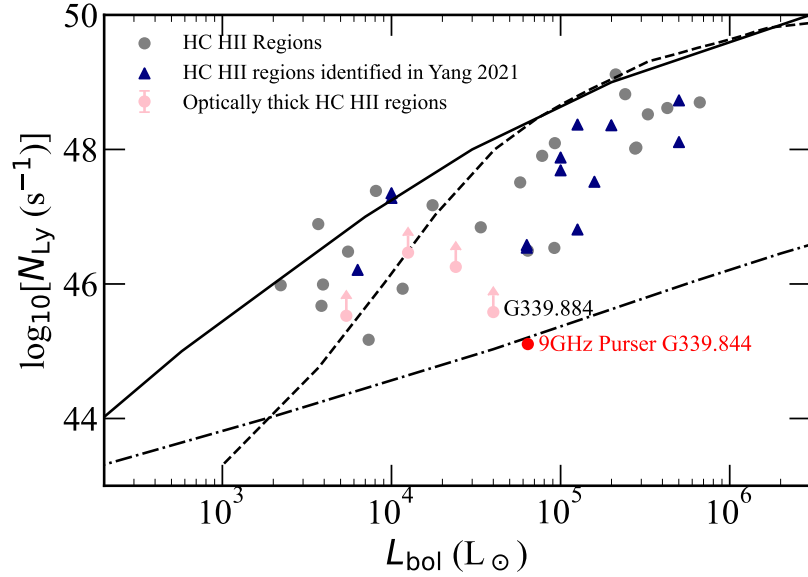


FIGURE 4.14: Lyman-continuum photon flux as a function of bolometric luminosity for the HC HII regions identified in this work and in the literature. The grey and pink circles show our sample of HC HII and optically thick HC HII regions, respectively. The blue triangles represent the HC HII and transition objects identified in Yang et al. (2021). The dashed line indicates the relationship for OB ZAMS-star models (Martins et al., 2005; Davies et al., 2011) and the dot-dashed line represents a fit to radio jets found in Purser et al. (2016, 2021). The solid black line corresponds to the Lyman continuum expected from a blackbody with the same radius and temperature as a ZAMS-star (see Sánchez-Monge et al. 2013b for more detail).

A key result of this work is that the HC HII regions identified here tend to be associated with lower-luminosity stars than those in previous HC HII region samples. This is shown in Figure 4.13, where the cumulative distributions of bolometric luminosity and Lyman-continuum flux are compared with the HC HII regions from Yang et al. (2021). The HC HII regions in this work are more frequently associated with early B-type stars, whereas the Yang et al. (2021) sample is dominated by sources ionised by late O-type stars. A two-sample Kolmogorov–Smirnov test indicates that the Lyman-continuum flux distributions are significantly different, while the bolometric luminosities show a marginal difference at the $\sim 2.8\sigma$ level.

This difference is also visible in Figure 4.14, where the HC HII regions identified in this work are shifted towards lower bolometric luminosities and lower Lyman-continuum fluxes. A plausible explanation is that previous HC HII region samples, particularly those selected at lower radio frequencies, are biased towards the brightest and most luminous sources. In contrast, the selection method used here begins

with methanol masers, which trace an early phase of high-mass star formation, and combines this with high-frequency, high-resolution radio observations. This approach is less biased towards bright, evolved radio sources and is therefore able to recover compact ionised regions around less luminous high-mass stars.

Despite this difference, the sources identified here remain consistent with the broader population of HII regions. In Figure 4.14, most sources lie well above the empirical radio-jet relation, supporting their interpretation as photoionised HII regions rather than ionised jets. The main exception is G339.884–1.259, which lies closer to the jet relation and is discussed in more detail below.

The trends discussed above indicate that this sample not only increases the number of known HCHII regions, but also extends the population to lower ionising luminosities than are commonly represented in previous samples. The optically thick HCHII regions are therefore of particular interest, as they are the most compact and embedded objects identified in this work. In the following section, we examine these sources individually to assess the evidence for ongoing accretion, feedback, and very recent ionisation.

4.4.2 PHYSICAL PROPERTIES OF THE OPTICALLY THICK HII REGIONS

Four HCHII regions in the sample remain optically thick at 24 GHz, with spectral indices $\alpha > 0.5$ and diameters < 0.05 pc. These sources are likely to represent the youngest ionised objects in the sample. All four radio sources lie within 1 arcsec of their associated methanol maser positions. Given the ~ 1 arcsec positional uncertainty of the MMB masers (Green et al., 2010), the radio and maser positions are considered coincident for the purposes of this discussion.

This close association is important because Class II methanol masers are thought to trace a short-lived early phase of high-mass star formation. They are radiatively pumped by infrared emission and require high-density, high-temperature environments (Sobolev & Deguchi, 1994). These conditions are expected to occur within the dusty molecular envelope, typically on scales of hundreds to thousands of au from the central

TABLE 4.7: Physical characteristics of the optically thick sources and their embedding environments. The typical error in the ATLASGAL clump properties are estimated to be of order 20 per cent.

Radio name	CSC name	ATLASGAL Clump Properties				Radio Derived Properties				
		Distance (kpc)	Mass ($10^2 M_\odot$)	Luminosity ($10^5 L_{\text{bol}}$)	Temperature (K)	Diameter (10^{-3} pc)	n_e (10^4 cm^{-3})	EM (10^7 pc cm^{-6})	$\log_{10} [N_{\text{Ly}}]$ (s^{-1})	ZAMS Spectral type
G326.475+0.703	AGAL326.474+00.702	2.6	8.4	5.4	20.7	3.2	7.2	1.8	45.5	B1
G332.987−0.487	AGAL332.986−00.489	3.5	40 ^a	24 ^c	24.6 ^a	1.4	118.9	195.3	46.3	B0.5
G333.029−0.063	AGAL333.029−00.061	2.8	2.5	12.5	30.8	2.6	50.9	68.6	46.5	B0.5
G339.884−1.259	AGAL339.884−01.257	2.1	4 ^b	40 ^d	—	2.5	17.9	5.3	45.5	B1

Note: references. ^a He et al. (2016), ^b Liu et al. (2019), ^c Wheelwright et al. (2012), ^d Zhang et al. (2019a).

high-mass protostar (Breen et al., 2013; Urquhart et al., 2015). The coincidence between the optically thick radio emission and methanol masers therefore suggests that these HC HII regions are still closely associated with the accretion environment of the forming massive star.

Additional maser species provide further information about the local environment. Water masers are collisionally pumped and require high densities ($\sim 10^7 \text{ cm}^{-3}$) and temperatures of several hundred K (Elitzur et al., 1992). They are commonly associated with shocked gas in molecular outflows (Claussen, 2002). OH masers can also trace shocked gas, particularly at the interface between ionised and molecular material, and may therefore be associated with a slightly later stage of evolution than Class II methanol masers (Frail & Mitchell, 1998; Beuther et al., 2019). The presence of these maser species, together with compact optically thick radio emission, provides evidence that these objects are young massive stars that are beginning to ionise their surroundings while still interacting strongly with their natal material.

The physical properties of the four optically thick sources and their embedding clumps are summarised in Table 4.7. Since these sources remain optically thick at 24 GHz, their Lyman-continuum fluxes and inferred ZAMS spectral types should be treated as lower limits.

G326.475+0.703 (Figure 4.15): The high-frequency radio emission from G326.475+0.703 is embedded towards the centre of the dense molecular clump AGAL326.474+00.702 (Urquhart et al., 2014c), associated with the RCW 95 massive star-forming region (Rodgers et al., 1960). The clump has been classified as an infrared dark cloud, SDC G326.476+0.706 (Peretto & Fuller, 2009), and has a mass of $840 M_\odot$ and volume den-

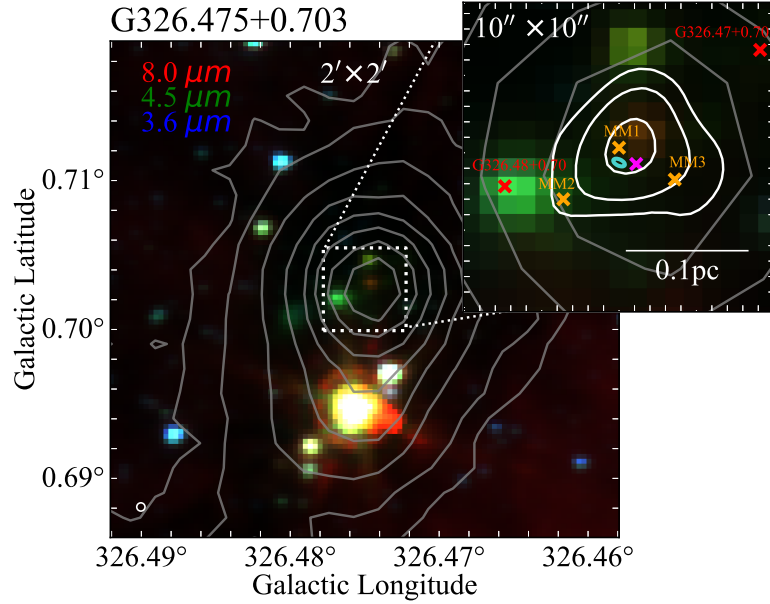


FIGURE 4.15: Three-colour composite images from Spitzer GLIMPSE 8- μm (red), 4.5- μm (green) and 3.6- μm (blue) bands for HCHII region G326.475+0.703. In the upper-right zoomed panel, the cyan ellipse shows the high-frequency (24-GHz) radio source and the magenta crosses show the position of the MMB methanol maser. The 870- μm dust emission from ATLASGAL is traced by the grey contours. The white contours show the 350-GHz dust continuum emission from SPARKS where the orange crosses mark the positions of the dense cores as identified in Csengeri et al. (2017). The red crosses show the peak position of EGOs as identified in Cyganowski et al. (2008).

sity of 10^6 cm^{-3} (Urquhart et al., 2014c). The central region is weak at 8 and 24 μm , although a brighter mid-infrared source is visible towards the south-east edge of the clump.

High-resolution 350 GHz dust-continuum observations by Csengeri et al. (2017) resolve the central region into three dense cores, MM1, MM2, and MM3, with masses of $150 M_{\odot}$, $27 M_{\odot}$, and $20 M_{\odot}$, respectively. The HCHII region and methanol maser are both coincident with the most massive core, MM1. At a distance of 2.6 kpc, the separation between the radio source, maser position, and core centre corresponds to approximately 1550 au, comparable to the scale of a high-mass protostellar accretion environment once positional uncertainties are considered.

Two extended green objects (EGOs) are located to the east and west of the central core (Cyganowski et al., 2008). These are shown in Figure 4.15. EGOs are commonly associated with excess 4.5 μm emission, which may trace shocked H_2 and CO emission from outflows (Reach et al., 2006). Their location, offset by approximately 8–10 arcsec from the central core, suggests that they may trace a bipolar molecular

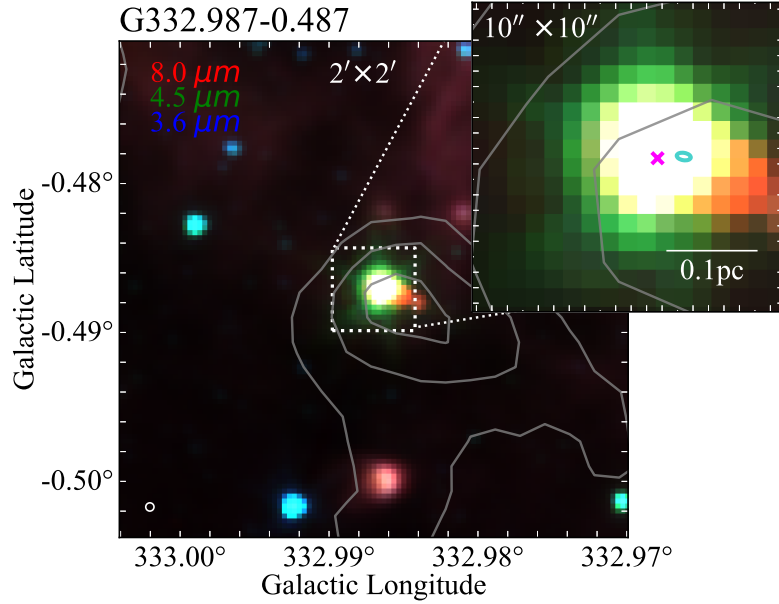


FIGURE 4.16: Three-colour composite images from Spitzer GLIMPSE 8- μm (red), 4.5- μm (green) and 3.6- μm (blue) bands for HCHII region G332.987–0.487. The 870- μm dust emission from ATLASGAL is traced by the grey contours. In the upper-right zoomed panel, the cyan ellipse shows the high-frequency (24-GHz) radio source and the magenta cross shows the position of the MMB methanol maser.

outflow. However, analysis of the ALMA CO(3–2) data from SPARKS does not reveal a clear outflow in the direction of the northern EGO, so the nature of this emission remains uncertain.

Although the source is weak at 8 and 24 μm , strong 70 μm emission is detected in the Hi-GAL data (Molinari et al., 2010b), leading to its classification as protostellar by Urquhart et al. (2022). The combination of a dense central core, methanol maser emission, possible shocked outflow tracers, and compact optically thick radio emission suggests that a high-mass protostar is actively forming within MM1 and has recently begun to ionise its surroundings. The radio-derived Lyman-continuum flux and bolometric luminosity are consistent with a ZAMS spectral type of B1 or earlier, corresponding to a stellar mass greater than $10 M_{\odot}$.

G332.987–0.487 (Figure 4.16): G332.987–0.487 is a compact radio source with an angular size comparable to the synthesised beam (~ 0.4 arcsec). It is embedded near the centre of AGAL332.986–00.489 (Contreras et al., 2013), which lies within the G333 giant molecular cloud. This cloud is located at a distance of approximately 3.6 kpc (Lockman, 1979) and is one of the most active star-forming regions in the

Galaxy (Urquhart et al., 2014a). Ammonia observations by Billington et al. (2019a) identify a dense central region with a size of approximately 0.2 pc. The radio emission is coincident with both the ammonia and ATLASGAL peaks, and lies within 0.7 arcsec of the associated methanol maser (Caswell, 2010).

The mid-infrared environment contains a bright $8\mu\text{m}$ point source associated with extended $4.5\mu\text{m}$ emission. This source has been classified as a MYSO by the RMS survey (Lumsden et al., 2013) and by ATLASGAL (Urquhart et al., 2022). Near-infrared spectroscopy by Ilee et al. (2013) detected CO bandhead emission towards this MYSO. CO bandhead emission traces warm, dense gas in the inner regions of accretion discs (Wheelwright et al., 2012; Ilee et al., 2013). Together with the methanol maser, this provides evidence for ongoing accretion.

The MYSO associated with this source, G332.9868–00.4871, was modelled by Ilee et al. (2013), who derived a stellar mass of $16.6 M_{\odot}$ and an effective temperature of 30,000 K. These values are consistent with a B0.5 ZAMS-star, in agreement with the ionising photon flux derived from the radio data. The angular offset between the HC HII region and the MYSO is approximately 0.3 arcsec, and they are therefore considered to be associated with the same object.

G333.029–0.063 (Figure 4.17): G333.029–0.063 is a very compact source located towards the centre of AGAL333.029–00.061 (Contreras et al., 2013), also within the G333 giant molecular cloud (Lockman, 1979). The mid-infrared image reveals several point sources, suggesting a small protocluster within the central region of the clump. The peak of the dust emission itself remains mid-infrared dark. The high-frequency radio source is coincident with the edge of the brightest mid-infrared source, which is extended and located south of the clump centre.

CORNISH-South 5 GHz observations reveal an unresolved radio counterpart, G333.0290–0.0631, offset by approximately 0.5 arcsec from the high-resolution source (Irabor et al., 2023). Given the resolution and positional uncertainties of the 5 GHz data, the two radio detections are likely to be associated with the same ionising source. The extended $8\mu\text{m}$ emission and 5 GHz radio counterpart led to this object being classified as an HII region in the RMS survey (Lumsden et al., 2013).

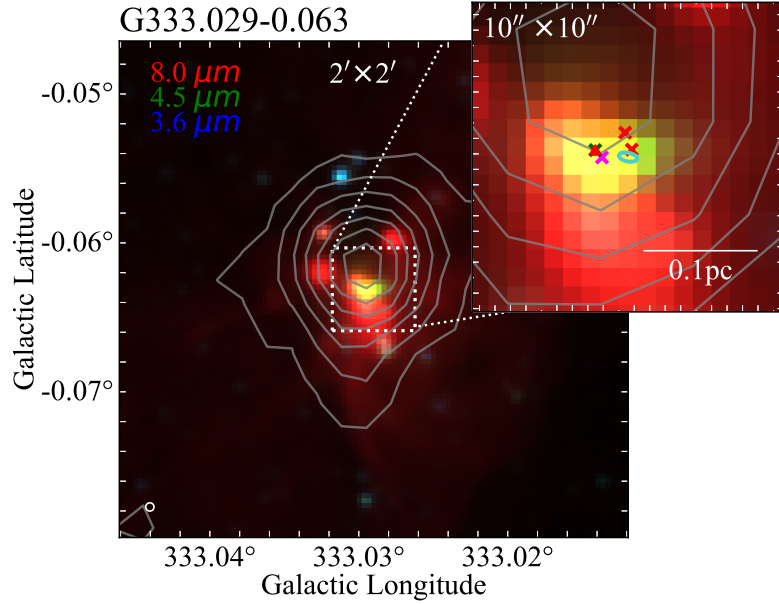


FIGURE 4.17: Three-colour composite images from Spitzer GLIMPSE 8- μm (red), 4.5- μm (green) and 3.6- μm (blue) bands for HC II region G333.029–0.063. The 870- μm dust emission from ATLASGAL is traced by the grey contours (Schuller et al., 2009). In the upper-right zoomed panel, the cyan ellipse shows the high-frequency (24-GHz) radio source and the magenta cross shows the position of the MMB methanol maser. The 5-GHz CORNISH-South radio source is shown as a red triangle (Irabor et al., 2023). OH and H₂O masers are shown as red and green crosses, respectively (Qiao et al., 2020; Breen & Ellingsen, 2011).

Methanol, H₂O, and OH masers are all detected within 3 arcsec of the HC II region. The H₂O maser lies north-east of the methanol maser, which is coincident with the 5 GHz radio emission. Two OH masers have also been identified towards this region by the SPLASH survey (Dawson et al., 2014; Qiao et al., 2020). The close association between the compact radio emission and multiple maser species suggests that the embedded high-mass object is still interacting with dense molecular gas. The H₂O maser indicates shocked gas, likely associated with an outflow, while the OH masers may trace shocked material near the boundary of the expanding ionised region. Together, these features suggest that the source has recently begun ionising its surroundings while still retaining signatures of active feedback.

G339.884–1.259 (Figure 4.18): G339.884–1.259 is detected towards the centre of the dense molecular clump AGAL339.884–01.257 (Contreras et al., 2013), at a distance of 2.1 ± 0.4 kpc (Krishnan et al., 2015). High-resolution mid-infrared imaging with OSCIR at Keck resolved the emission into three peaks, labelled 1A, 1B, and 1C, within a region of approximately 3000 au (De Buizer et al., 2002). ALMA 1.3 mm observations

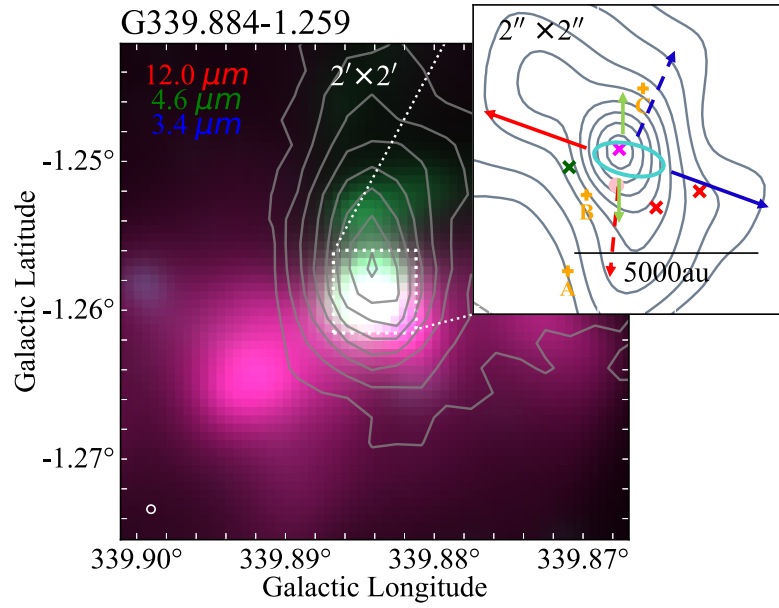


FIGURE 4.18: Three-colour composite images from WISE 12- μm (red), 4.6- μm (green) and 3.4- μm (blue) bands for HC HII region G339.884–1.25. The 870- μm dust emission from ATLASGAL is traced by the grey contours. In the upper-right zoomed panel, the cyan ellipse shows the position of the high-frequency (24-GHz) radio source and the magenta cross shows the position of the MMB methanol maser. OH and H₂O masers are shown as red and dark green crosses, respectively (Qiao et al., 2020; Breen & Ellingsen, 2011). The 10- μm peak positions are shown as orange plus symbols. The SPARKS 1.3-mm continuum emission is traced by the dark grey contours. The dotted and dashed arrows show red-shifted and blue-shifted CO outflows reported in Zhang et al. (2019a). The lime green arrows represent the ionised jet as identified in Purser et al. (2016).

by Zhang et al. (2019a) reveal a dense core with a gas mass of 23–58 $M_{\odot}$, depending on the assumed dust temperature. The HC HII region and methanol maser are both coincident with the centre of this core. Interestingly, the millimetre peak does not coincide with any of the mid-infrared peaks, but instead lies between sources 1B and 1C, suggesting that the central object may still be deeply embedded.

Several maser species are detected towards the core. Two 1720 MHz OH masers lie to the south-west of the radio emission, offset by approximately 1 arcsec (Caswell et al., 1995), while an H₂O maser is located 0.7 arcsec east of the radio source. ALMA ¹²CO(2–1) observations reveal a large-scale molecular outflow with a north-east–south-west orientation, as well as a secondary weaker outflow in a south-east–north-west direction (Zhang et al., 2019a). The secondary outflow is approximately aligned with an ionised radio jet reported by Purser et al. (2016). The presence of multiple outflow axes has been interpreted as evidence for an embedded proto-binary system (Zhang et al., 2019a).

This source is the most ambiguous of the four optically thick HC HII regions. Comparing the high-frequency flux densities measured in this work with those reported by Purser et al. (2016), we find that the flux densities are approximately a factor of two higher. The calibration was checked using the primary flux calibrator and found to be consistent with expected values within 10 per cent. The difference may therefore reflect variability between the 2011 observations of Purser et al. (2016) and the observations presented here. Variability has been reported for compact and young HII regions in the GLOSTAR survey (Yang et al., 2023), and may be relevant in this case.

Using their 9 GHz flux density, Purser et al. (2016) found that this source was consistent with the radio luminosity expected for an ionised jet. However, if the source is optically thick at 9 GHz, the radio luminosity would be underestimated. The 24 GHz flux density measured in this work places the source above the empirical radio-jet relation in Figure 4.14, making an HC HII region interpretation plausible. Nevertheless, given the evidence for outflows, possible jet emission, and variability, the true nature of G339.884–1.259 remains uncertain.

Overall, the four optically thick HC HII regions show several characteristics ex-

pected for very young ionised objects: compact radio emission, high electron densities, close positional association with methanol masers, and embedded locations within dense molecular material. In several cases, additional maser species, outflow tracers, or mid-infrared/submillimetre structure indicate that accretion and feedback are still active. These properties support the interpretation that the optically thick sources represent some of the youngest HII regions in the sample. More broadly, the results demonstrate that high-frequency, high-resolution observations towards methanol maser sites can identify HC HII regions around relatively lower-luminosity massive stars, extending the known population beyond the brightest examples commonly selected in previous radio surveys.

4.5 CONCLUSIONS

This chapter has presented high-resolution, high-frequency radio continuum observations towards a sample of compact HII region candidates identified in Chapter 3. These sources were selected on the basis of being unresolved and/or optically thick between 5 and 23.7 GHz, and for their association with methanol masers. The aim of this work has been to confirm the nature of these sources and to test whether this selection method is effective at identifying the youngest and most compact HII regions.

From the 39 observed fields, 27 reliable radio detections are identified above the 3σ level. By combining these data with archival radio observations from CORNISH-North, CORNISH-South, MAGPIS, and THOR, spectral energy distributions are constructed spanning 5–24 GHz where possible. These SEDs are used to derive physical properties, including source size, electron density, emission measure, Lyman-continuum photon flux, and turnover frequency, assuming a homogeneous and ionisation-bounded HII region model.

The derived physical properties show that the sample spans a range of evolutionary stages. A total of 14 sources satisfy the criteria for HC HII regions, although one of these, G339.884–1.259, is also consistent with an ionised jet and is therefore

treated as ambiguous. A further six sources are classified as transition objects between the HC HII and UC HII stages, and six sources are identified as UC HII regions. The majority of the HC HII regions identified in this work are newly reported, and one source is found to be mid-infrared dark at $24\mu\text{m}$ suggesting a deeply embedded and potentially very early evolutionary stage.

The properties of the HC HII regions indicate that they are typically smaller, denser, and associated with lower ionising luminosities than those found in previous studies. In many cases, the inferred spectral types are consistent with early B-type stars, rather than the late O-type stars that dominate earlier samples. This reflects the methanol-maser-based selection used in this work, which is sensitive to younger and less evolved systems and is therefore able to recover compact ionised regions around lower-luminosity massive stars.

The youngest sources in the sample are deeply embedded within dense molecular clumps and show strong associations with methanol masers, as well as additional tracers such as H_2O and OH masers, molecular outflows, and extended green objects. These associations suggest that ionisation is occurring while accretion and feedback processes are still ongoing. In particular, four sources remain optically thick at 24 GHz and are likely to represent the earliest stages of HII region development identified in this study.

Overall, these results demonstrate that high-frequency, high-resolution observations towards methanol maser sites provide an effective way to identify HC HII regions across a broader range of stellar masses and evolutionary stages than is typically accessible through lower-frequency radio surveys. This approach not only confirms the nature of the candidates identified in Chapter 3, but also extends the known population of HC HII regions towards lower ionising luminosities.

This chapter represents the second stage of the SCOTCH approach, in which an initial low-resolution survey is followed by targeted high-resolution observations to confirm and characterise compact HII regions. The success of this method motivates its application to a larger and more complete sample. In the following chapter, this approach is extended to the remaining MMB methanol masers in the southern Galactic plane, using a combination of low-resolution observations to identify candidate sources

and high-resolution follow-up to determine their physical properties.

CHAPTER 5

SCOTCH III – THE COMPLETE SEARCH FOR HYPERCOMPACT HII REGIONS IN THE FOURTH QUADRANT

5.1 INTRODUCTION

As outlined in Chapters 3 and 4, embedded HII regions provide a key observational window into the earliest stages of high-mass star formation (Wood & Churchwell, 1989b; Kurtz et al., 1994; Churchwell, 2002; Kurtz, 2005a; Giveon et al., 2005b). These compact regions of ionised gas form as newly born massive stars begin to ionise their surrounding material, and their small sizes, high densities, and optical depths make them particularly valuable probes of the transition between the protostellar and main-sequence phases.

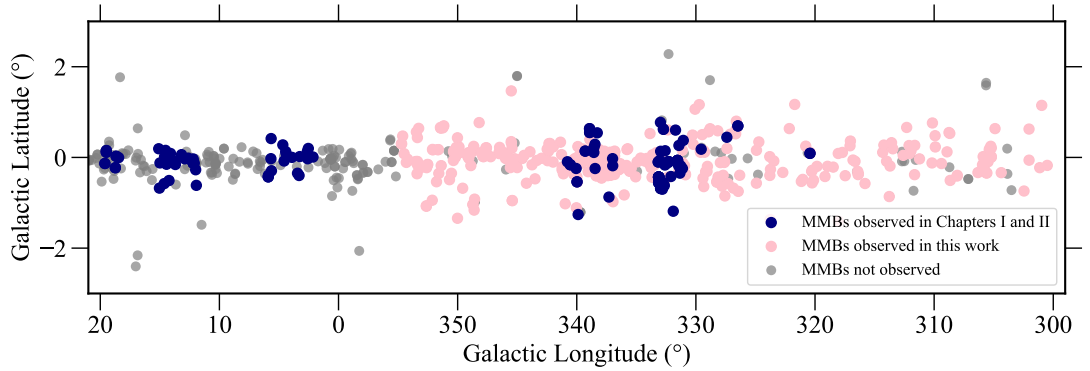


FIGURE 5.1: The distribution of MMB methanol masers in the region covered by SCOTCH. The blue filled circles represent the MMB masers observed in Chapters 3 and 4, while the pink filled circles are the methanol masers observed in this work. Grey circles have not been observed.

The results presented in the preceding chapters have demonstrated that Class II methanol masers are robust tracers of these young, deeply embedded systems. In Chapter 3, a large sample of candidate HII regions was identified through low-resolution, high-frequency radio observations, providing an initial census of compact ionised emission associated with methanol maser sites. Chapter 4 then presented high-resolution follow-up observations, confirming the nature of these sources and establishing a reliable methodology for distinguishing between hypercompact, ultracompact, and more evolved HII regions. Together, these studies have demonstrated that the combination of methanol maser selection and high-frequency radio continuum observations provides a powerful and efficient means of identifying the youngest ionised regions. However, the samples presented in Chapters 3 and 4 do not yet provide complete coverage of the southern Galactic plane. In particular, the fourth quadrant ($300^\circ \leq \ell \leq 355^\circ$) has not previously been systematically explored at comparable angular resolution and frequency. This incomplete coverage limits our ability to assess the full population of hypercompact HII regions and introduces potential biases when interpreting their Galactic distribution and physical properties.

Building on the framework established in the earlier chapters, this work represents the final stage of the SCOTCH survey. Here, we apply the same observational strategy and analysis techniques to the remaining methanol maser sites in the fourth quadrant, completing the search for hypercompact HII regions across the southern Galactic plane. By extending the sample in this way, we aim to construct a more

TABLE 5.1: Summary of the observation dates array configurations used and the number of sources observed at each epoch.

Array config.	Date	# of Obs.
H214	27/06/2022	84
	06/07/2022	80
	15/07/2022	85
	22/07/2022	88
6A	01-03/08/2023	67

uniform and statistically robust census of compact HII regions, enabling a more comprehensive investigation of their physical properties, evolutionary states, and Galactic distribution.

Figure 5.1 shows the distribution of all MMB methanol masers within the region covered by the SCOTCH survey. The blue filled circles indicate the maser sites observed in Chapters 3 and 4, while the pink filled circles mark those targeted in this work. Sources shown in grey have not been observed as part of the SCOTCH programme. This expanded sample enables a uniform assessment of the Galactic distribution and physical properties of hypercompact HII regions across the southern Galactic plane, reducing selection biases present in earlier studies and providing a more complete framework for understanding their evolutionary sequence.

5.2 OBSERVATIONS AND DATA REDUCTION

In this section, we describe the observational strategy and data reduction procedures used to complete the SCOTCH survey in the fourth quadrant. The methodology follows the same two-stage approach established in Chapters 3 and 4, consisting of an initial low-resolution survey to identify candidate sources, followed by targeted high-resolution observations to resolve their structure and confirm their nature. Only a brief overview is provided here, with full details of the procedures given in Chapter 2.

TABLE 5.2: Summary of low- and high-resolution observational parameters.

Parameter	Array config.	
	H214	6A
Frequency	18 & 24 GHz	18 & 24 GHz
Primary beam (FWHM)	2'6	2'6
Synthesised beam ^a (FWHM)	$\sim 5''.25 \times 6''.89$	$\sim 0''.36 \times 0''.49$
Shortest and longest baseline	82 & 247 m	337 & 5939 m
Largest angular scale θ_{LAS}	$\sim 40''$	$\sim 10''$
Total on-source integration time	~ 10 mins	~ 30 mins

^a The sizes and shapes of the synthesised beam are dependent on the declination of the source. The values presented here correspond to the average declination (-48°) of our sample and are provided as a guide.

5.2.1 OBSERVATIONAL SETUP

Radio continuum observations were carried out during July 2022 and August 2023 using the ATCA. Consistent with the method adopted in Chapter 4, observations were performed at frequencies of 18 GHz and 24 GHz, corresponding to wavelengths of approximately 1.7 and 1.4 cm, respectively. These high-frequency bands are well suited to the study of compact HII regions, as they reduce contamination from water maser emission while remaining sensitive to dense, optically thick ionised gas.

Two array configurations were used to replicate the two-stage observational strategy developed in Chapters 3 and 4. The hybrid H214 configuration was used to obtain low-angular resolution (~ 20 arcsec) observations of the full sample, enabling the initial identification of compact and optically thick candidates. These were followed by high-angular resolution (~ 0.5 arcsec) observations using the 6A configuration, allowing the detailed structure of selected sources to be resolved. This two-stage approach enables both the identification of candidate compact sources and the resolution of their intrinsic structure, limiting the effects of spatial filtering in interferometric observations.

The CABB was configured in the same manner as described in Chapter 4, with two 2 GHz continuum bands, each divided into 32 channels of 64 MHz. The bands were centred at 18 and 24 GHz, providing continuous frequency coverage from 17–19 GHz and 23–25 GHz. A summary of the observing dates, array configurations, and number of sources observed is provided in Table 5.1.

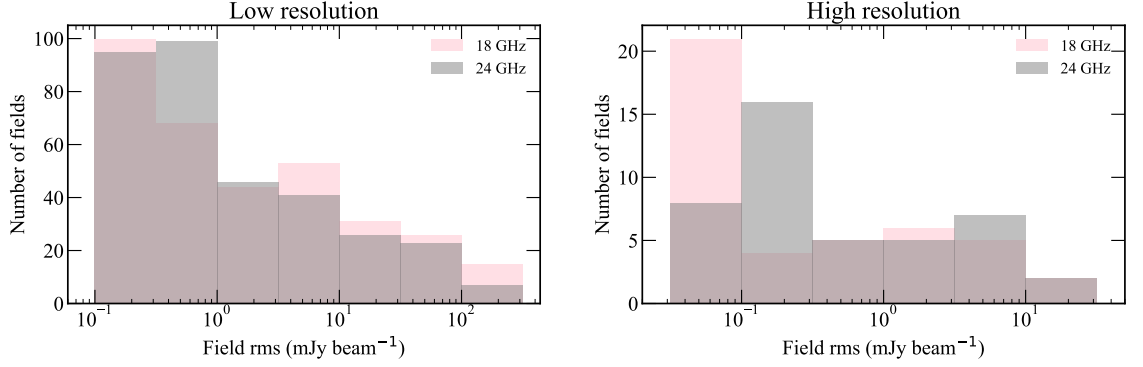


FIGURE 5.2: Histograms of the number of fields observed as a function of the map rms noise at both frequencies and resolutions. The data have been binned using a value of 0.5 dex.

The low-resolution observations were obtained over four observing sessions in June and July 2022, while the high-resolution follow-up was conducted over three days in August 2023. The observational parameters for both configurations are summarised in Table 5.2. Each field was observed using five or six short (~ 2 min) integrations distributed over a range of hour angles to improve the uv -coverage.

Calibration was performed using standard ATCA procedures. Each observing block was bracketed by short (~ 1 min) observations of a nearby phase calibrator (typically within 10°) to correct for time-dependent atmospheric and instrumental variations. The primary flux calibrator (1934–638) and bandpass calibrator (1253–055) were observed once per observing session for approximately 10 minutes each, providing absolute flux density scaling and bandpass calibration.

The total on-source integration time differs between the two datasets. The low-resolution observations achieve approximately 10 minutes per field, while the high-resolution observations reach approximately 30 minutes per field through multi-day integration. This improved sensitivity is sufficient to detect HII regions powered by ZAMS stars of spectral type B0.5 or earlier at distances of up to 20 kpc (Anderson et al., 2014). Figure 5.2 shows the distribution of rms noise values for both the low- and high-resolution datasets.

5.2.2 SOURCE SELECTION AND OBSERVATIONAL STRATEGY

A total of 452 MMB methanol maser sites are located within the longitude range $300^\circ \leq \ell \leq 355^\circ$ (Green et al., 2009). Sources within the Galactic centre region ($355^\circ \leq \ell \leq 5^\circ$) were excluded, as reliable kinematic distances are not available in this region, limiting the ability to derive physical properties.

To avoid duplication, 57 sources previously observed in Chapter 3 were excluded, along with 36 masers lacking ATLASGAL counterparts. The remaining sources were grouped spatially to optimise the observing strategy. In cases where multiple masers lie within the ATCA primary beam (~ 2 arcmin), they were observed simultaneously within a single pointing. This resulted in 335 unique fields, including 24 cases where pairs of masers are separated by less than 30 arcsec. This selection strategy ensures that the final sample is both observationally efficient and physically meaningful, retaining sources with well-constrained environments while minimising biases introduced by incomplete data.

Low-resolution observations were obtained for all 335 fields. Following the analysis of these data, 42 sources were identified as compact and/or optically thick candidates and selected for high-resolution follow-up. These sources satisfy the criteria expected for hypercompact HII regions (i.e., compact morphology and optically thick emission between 5–18 GHz), making them well suited for detailed structural and physical analysis.

The observational parameters for the full sample are summarised in Table 5.3. As in previous chapters, the use of an identical correlator setup for both configurations allows the datasets to be combined during imaging, improving sensitivity and uv -coverage.

5.2.3 DATA REDUCTION AND IMAGING

Data calibration and reduction were performed using the MIRIAD software package (Sault et al., 1995b), following the standard ATCA procedures described in Chapter 2. The raw visibility data were first inspected and iteratively flagged to remove RFI and corrupted data. This process included the identification of artefacts such as sidelobe

TABLE 5.3: Observational field parameters from all observed fields. The field names and pointing centres of the observations are based on the MMB names and positions.

Field name	RA		Dec. (J2000) (d:m:s)	Low Resolution				High Resolution				
	(J2000) (h:m:s)	(J2000) (d:m:s)		rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)	Position angle (°)	rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)
G300.504−00.176	12:30:03.57	−62:56:48.8	3.1	Y	10	8.8	−86	2.4	−	7.5	6.7	79
G300.969+01.148	12:34:53.28	−61:39:39.9	40	Y	10	8.8	89	33	Y	7.5	6.8	74
G301.136−00.226	12:35:35.13	−63:02:32.6	59	Y	10	8.8	−85	58	Y	7.5	6.8	78
G302.032−00.061	12:43:31.92	−62:55:06.6	56	Y	10	8.9	88	41	Y	7.6	6.9	78
G302.034+00.625	12:43:43.44	−62:13:58.4	0.11	Y	9.9	9.1	−78	0.14	N	7.6	6.7	86
G302.455−00.741	12:47:08.64	−63:36:30.2	0.29	N	9.9	9.3	−76	0.19	N	7.6	6.8	85
G304.367−00.336	13:04:09.81	−63:10:20.2	0.13	N	10	9.1	−89	0.15	N	7.4	6.9	−80
G304.887+00.635	13:08:11.95	−62:10:21.7	0.12	N	9.9	9.1	−82	0.17	N	7.5	6.7	−75
G305.199+00.005	13:11:17.20	−62:46:45.8	51	N	9.3	8.7	−64	13	N	7	6.5	−57
G305.200+00.019	13:11:16.92	−62:45:55.0	100	N	9.3	8.6	−59	60	N	7	6.5	−47
G305.208+00.206	13:11:13.70	−62:34:41.5	21	Y	9.1	8.6	−62	9.2	−	6.9	6.6	−35
G305.248+00.245	13:11:32.47	−62:32:09.2	14	N	9.2	8.6	−84	5.3	N	6.8	6.5	−33
G305.362+00.150	13:12:35.85	−62:37:17.7	15	Y	9.1	8.6	−73	7.7	−	6.9	6.5	−31
G305.366+00.184	13:12:36.74	−62:35:14.6	79	N	9.1	8.6	−64	45	N	6.9	6.6	−21
G305.475−00.096	13:13:45.74	−62:51:28.4	0.47	N	9.1	8.7	−42	0.6	N	7.1	6.6	−5.9
G305.563+00.013	13:14:26.90	−62:44:29.4	9.1	Y	9.2	8.7	−20	4.9	−	7.2	6.4	−8.8
G305.573−00.342	13:14:49.12	−63:05:38.4	0.32	N	9.9	8.3	−7.9	0.48	N	7.2	6.3	−8
G305.615−00.344	13:15:11.30	−63:05:29.7	0.23	N	9.7	9	22	0.29	N	7.4	6.4	24
G305.799−00.245	13:16:43.22	−62:58:32.8	1.8	Y	9.6	9	26	1.3	Y	7.4	6.4	23
G305.822−00.115	13:16:48.72	−62:50:38.0	0.19	N	9.7	8.9	30	0.22	N	7.3	6.4	25
G305.887+00.017	13:17:15.52	−62:42:23.0	0.29	Y	9.8	8.8	28	0.23	N	7.2	6.4	36
G305.940−00.164	13:17:53.04	−62:52:50.5	0.15	N	9.9	8.8	29	0.23	N	7.1	6.4	42
G306.322−00.334	13:21:23.01	−63:00:29.5	3.2	N	10	8.7	25	1.3	N	7.3	6.3	29
G308.056−00.396	13:36:32.16	−62:49:05.5	12	Y	9.5	9.1	38	9.9	Y	7	6.6	30
G308.075−00.411	13:36:43.51	−62:49:45.1	8.6	N	9.5	9	18	3.8	N	7.3	6.5	32

Note: only a small portion of the data is provided here, the full table is available in Chapter 7.3 of the appendix.

TABLE 5.4: Extracted source parameters from our detected radio sources at low resolution. Column 1 is the radio name, which is a combination of Galactic longitudes and latitudes determined by fitting ellipsoidal Gaussians using IMFIT, Columns 2 and 3 are the Right Ascension and Declination of each source, respectively. Columns 4-10 present 18-GHz source parameters and columns 11-17 present 24-GHz source parameters. Col 8–10 and 15–17 are the deconvolved major, minor and position angle, respectively. Sources with – are those for which sizes could not be deconvolved. Sources with a † indicate those with a poor synthesised beam.

24GHz														
Radio name	f_{peak} (mJy beam ⁻¹)	Δf_{peak} (mJy beam ⁻¹)	f_{int} (mJy)	Δf_{int} (mJy)	Major (arcsec)	Minor (arcsec)	PA ($^{\circ}$)	f_{peak} (mJy beam ⁻¹)	Δf_{peak} (mJy beam ⁻¹)	f_{int} (mJy)	Δf_{int} (mJy)	Major (arcsec)	Minor (arcsec)	PA ($^{\circ}$)
G300.504−0.173	36	0.85	54	2.2	7.8	5.2	8.8	24	0.47	47	2.2	8	6.1	18.6
G300.969+1.148	500	12	580	30	4.8	2.4	−44.6	490	35	560	79	3.7	1.6	−50
G301.136−0.225	870	33	1100	84	6.5	0.9	0.4	1000	110	1400	300	6.8	1.5	−4.4
G302.032−0.061	830	15	970	28	4.7	2.8	−37.6	670	15	840	35	4.2	2.7	−40.1
G302.033+0.626	0.48	0.052	0.45	0.08	—	—	—	0.84	0.07	0.78	0.1	—	—	—
G305.199+0.206	110	2	190	11	9.4	5.7	87.1	53	2.2	68	6.2	4.5	2.4	87.9
G305.215+0.200	130	3.3	240	19	10.2	6	77.7	46	1.2	83	5.8	8	4.1	−65.6
G305.359+0.151	91	1.9	140	9.4	7.8	4.6	18.7	61	1.6	89	6.4	7.3	0.8	−31.5
G305.562+0.013	50	3.8	54	8	—	—	—	41	2.5	45	4.5	—	—	—
G305.798−0.242	9.7	0.44	12	1.2	—	—	—	8.5	0.64	11	1.4	4.2	2.6	−22.2
G305.800−0.251	19	0.62	29	1.4	6.9	6.2	−82.8	11	0.89	24	3	7.6	7.5	−89.8
G305.886+0.017	1.1	0.097	3.8	1.5	23.2	6.8	−27.8	1.3	0.1	1.7	0.2	4.2	—	—
G308.0560.396	200	7.9	200	12	—	—	—	190	8.7	200	13	—	—	—
G308.6510.508	1.9	0.13	2.8	0.28	9.8	3.7	22.7	2.9	0.38	3.3	0.7	4.3	2.1	38.2
G308.918+0.122	290	10	380	19	6.4	4.3	0.4	230	11	320	22	5.8	4.1	0.8
G309.3840.135	2.1	0.3	2.9	0.61	8.7	1.6	53.8	2.5	0.24	3.2	0.47	5.6	1.7	60.6
G309.920+0.479	920	35	1000	55	4.9	0.8	42.7	880	49	1000	85	5.3	0.6	37
G310.144+0.760	7.7	0.31	11	0.75	10.2	1.8	79.3	7	0.33	9	0.9	—	—	—
G311.6420.380	280	4.4	290	7.1	—	—	—	260	6.1	280	12	—	—	—
G312.307+0.661	40	0.79	41	1.3	—	—	—	39	0.63	40	1.1	1.7	0.7	50.9
G312.597+0.047	72	5	86	12	5.2	2.8	20.8	50	2.6	69	6.4	5.2	3.2	21.8
G314.220+0.272	26	1.3	27	2.3	—	—	—	23	1.5	26	2.9	—	—	—

Note: only a small portion of the data is provided here, the full table is available in Chapter 7.3 of the appendix.

contamination from bright off-axis sources, large-scale ripples caused by incomplete *uv*-coverage, and degraded beam shapes. Particular care was taken in fields containing bright sources, where dynamic range limitations can increase the local noise and introduce deconvolution artefacts.

Following flagging, the data were calibrated using the primary flux, bandpass, and phase calibrators, and the resulting calibration solutions were applied to the target fields. Imaging was carried out using the MIRIAD tasks `INVERT`, `CLEAN`, and `RESTOR`. A Briggs robust weighting of 0.5 was adopted to provide a balance between sensitivity and angular resolution. Deconvolution was performed using several hundred `CLEAN` components, or until the residuals reached the noise level.

The low-resolution data were imaged over the full primary beam using a pixel size of 1 arcsec, resulting in images of approximately 2.1×2.1 arcmin. For the 42 fields with high-resolution observations, the low- and high-resolution visibility data were combined prior to imaging. This improves the sensitivity to both compact and moderately extended emission by enhancing the *uv*-coverage. These combined datasets were imaged using a pixel size of 0.2 arcsec, producing maps with angular extents of approximately 25×25 arcsec.

All images were corrected for the primary beam response. The rms noise for each field was estimated from emission-free regions near the centre of the image. The distribution of rms values for both datasets is shown in Figure 5.2. Variations in rms noise are primarily driven by dynamic range limitations, with higher noise levels observed in fields containing bright sources. The typical dynamic range of the maps is approximately 80. A detailed description of the data reduction procedures is provided in Chapter 2. The calibrated and imaged datasets produced here form the basis for the source identification and physical analysis presented in the following sections.

5.3 RESULTS

In this section, we present the results of the SCOTCH observations in the fourth Galactic quadrant. The analysis follows the two-stage approach established in Chapters 3 and 4: an initial identification of radio continuum sources in the low-resolution maps, followed by the selection and high-resolution confirmation of compact, optically thick HII region candidates. We then derive the physical properties of these sources and classify them according to their evolutionary stage. This provides the fourth-quadrant contribution to the final SCOTCH sample and establishes which candidates are suitable for comparison with the wider population of compact HII regions.

5.3.1 LOW-RESOLUTION SOURCE DETECTION

The final reduced low-resolution maps were examined for compact, high surface-brightness radio emission using a nominal detection threshold of 3σ , where σ is the local rms noise. All candidate detections were visually inspected to confirm the presence of discrete sources and to exclude imaging artefacts arising from sidelobes or poorly sampled extended emission.

A total of 121 radio sources were identified across 116 of the 335 observed fields, corresponding to a detection rate of ~ 30 per cent. The majority of detections (78 fields) consist of single point-like sources, while 32 fields contain a single extended source. Five fields exhibit two distinct radio sources, and in one case (G318.050+00.087) the emission is complex and cannot be reliably constrained. Representative examples of these morphologies are shown in Fig. 5.3.

Source parameters, including positions, peak and integrated flux densities, and angular sizes, were derived using the MIRIAD task IMFIT. For each source, a polygon was manually drawn around the emission to constrain the fit to the relevant structure and minimise contamination from nearby noise, artefacts, or unrelated emission. A consistent fitting procedure was applied to all detections, following the methodology established in Chapters 3 and 4. The derived parameters are presented in Table 5.4.

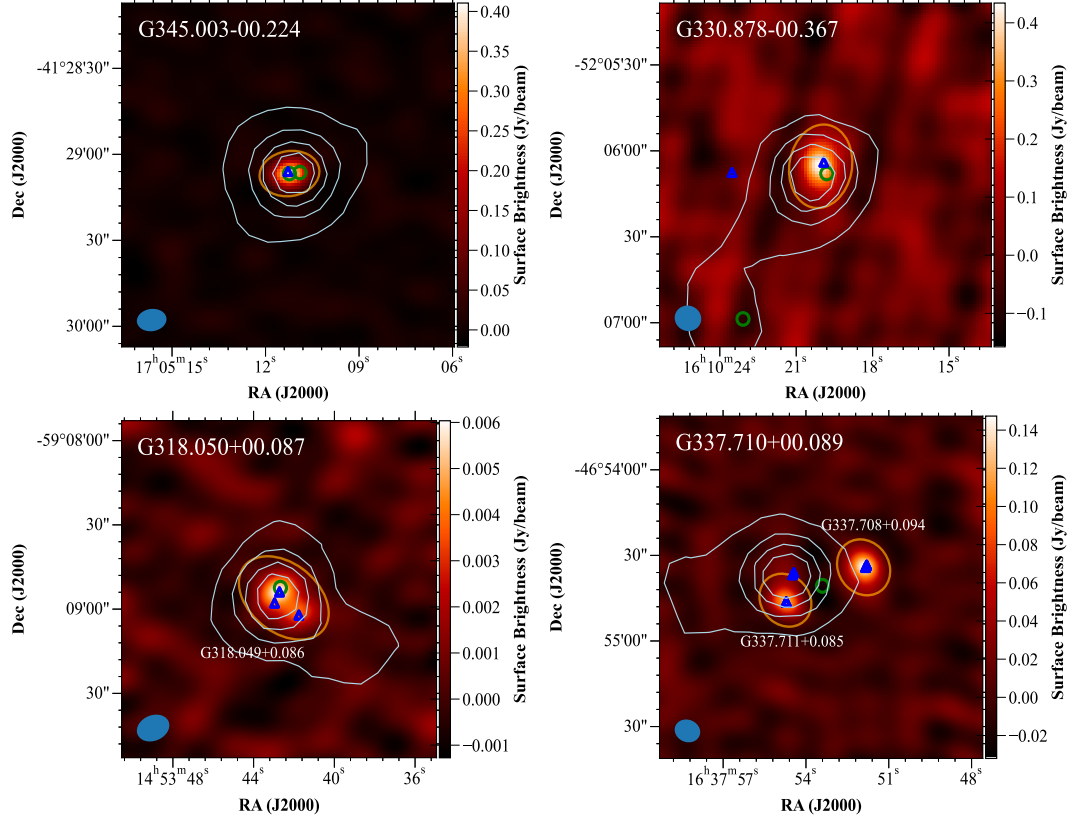


FIGURE 5.3: Examples of four 18 GHz radio maps with different emission types. The orange ellipse shows the resulting fit to the radio emission, while the green circles show the position of the methanol maser(s) located in the field. The blue triangles show the position of any low-frequency (5 GHz) radio counterparts. The grey contours trace the $870\ \mu\text{m}$ dust emission from ATLASGAL (Schuller et al. 2009). The filled blue ellipse in the bottom left-hand corner of each image indicates the size and orientation of the synthesised beam. The top left panel presents a single point source (G345.004–0.224), the top right panel shows an example of a single extended radio source (G330.878–00.367), the bottom left panel shows the multi-peaked radio source (G318.049+0.086), and the bottom right panel shows an example of a field with two radio sources (G337.708+0.094 & G337.711+0.085). The field name is given in the top left and the radio name is provided if it differs from the field name.

5.3.2 SELECTION OF COMPACT HII REGION CANDIDATES

To identify sources associated with active star formation, we examined the spatial correlation between the detected radio emission and known tracers, including 6.7 GHz methanol masers (MMB), 870 μm dust emission from ATLASGAL, and 5 GHz radio continuum emission from the literature. Visual inspection of multi-wavelength overlays was used to assess positional associations.

Of the 121 radio detections, 80 are coincident with both methanol masers and ATLASGAL dust emission, indicating that they are embedded within dense star-forming clumps. Based on ATLASGAL classifications (Urquhart et al., 2014c, 2018, 2022), 54 of these sources are associated with known HII regions, 13 with young stellar objects (YSOs), and four with protostellar clumps. Six are classified as photodissociation regions (PDRs), while three are associated with complex mid-infrared environments indicative of evolved HII regions. These latter three sources are excluded from further analysis, leaving a sample of 77 candidate HII regions.

However, positional association alone does not establish whether a source is young, compact, or optically thick. The radio spectral index therefore provides the next diagnostic. To further constrain the evolutionary stage of these candidates, we analysed their spectral properties using available 5 GHz data from CORNISH-South and MAGPIS. A total of 61 sources have 5 GHz counterparts, while six lie outside the survey coverage and 10 are undetected at this frequency.

To minimise the effects of spatial filtering, we restrict the analysis to compact 5 GHz sources with a y-factor ($f_{\text{int}}/f_{\text{peak}}$) less than 2. This yields a sample of 44 compact sources suitable for spectral index analysis. Spectral indices between 5 and 18 GHz were calculated following the method described in Chapter 3, while lower limits were derived for sources lacking 5 GHz detections.

Based on these measurements, 16 sources exhibit spectral indices consistent with optically thin emission ($-0.2 < \alpha < 0.3$), while 38 sources show rising spectra ($\alpha > 0.3$), indicative of optically thick emission. For the six sources without 5 GHz data, five display positive spectral indices between 18 and 24 GHz and are therefore also considered optically thick candidates. In total, 43 candidate radio sources, distributed

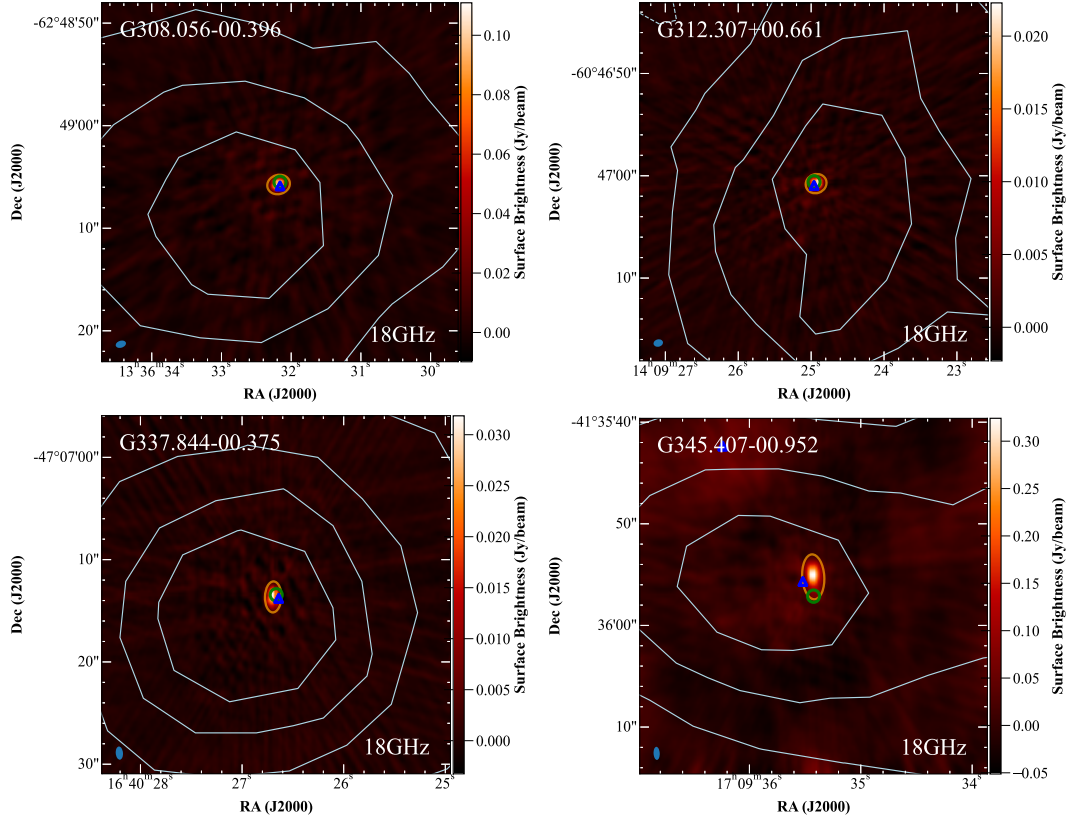


FIGURE 5.4: Examples of four high resolution 18 GHz radio detections. The top row presents radio sources G308.056–0.396 and G312.307+0.661. These are examples of compact radio sources (y -factor < 2). The bottom row presents radio sources G337.844–0.375 and G345.407–0.952, which are examples of compact but more resolved radio sources (y -factor < 4). The symbols are as described in Fig. 5.3.

across 42 fields, were selected for high-resolution follow-up.

5.3.3 HIGH-RESOLUTION DETECTIONS

High-resolution observations were obtained for the selected sample to resolve their structure and confirm their compact nature. Radio continuum emission above the 3σ threshold was detected in 41 of the 42 observed fields, yielding a total of 43 radio sources at 18 GHz.

Of these, 36 sources are detected at both 18 and 24 GHz, while seven are detected only at 18 GHz. The majority of detected sources are compact (y -factor < 2) or marginally resolved (y -factor < 4), consistent with expectations for young HII regions. Examples of high-resolution detections are shown in Fig. 5.4.

For the seven sources not detected at 24 GHz, a comparison between high-resolution integrated flux densities and low-resolution peak flux densities (Fig. 5.5)

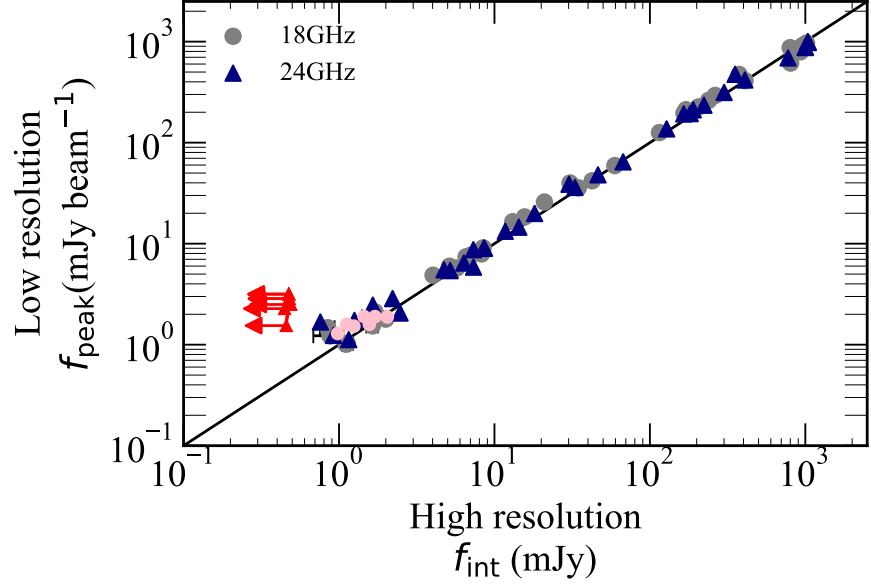


FIGURE 5.5: Distribution of integrated flux density from the high resolution study against peak flux densities from the low resolution study. Red upper limits indicate the seven 24 GHz non-detections, while filled pink points show the fluxes for the corresponding 18 GHz detections. The solid black line represents the line of equality.

reveals that a significant fraction of the flux is resolved out at higher resolution. This indicates that these sources are extended and not intrinsically compact. An additional source (G310.144+0.760) shows clear evidence of flux loss due to spatial filtering. In total, eight sources are classified as over-resolved and are excluded from further analysis.

The remaining 35 sources, which are detected at both frequencies and exhibit compact morphologies, form the final sample of confirmed compact HII region candidates.

5.3.4 RADIO SEDS AND PHYSICAL PROPERTIES

The physical properties of the 35 compact sources were derived by modelling their radio SEDs. Where available, 5 GHz flux densities from CORNISH-South and MAGPIS were incorporated to extend the frequency coverage. A total of 32 sources have usable 5 GHz information, including both detections and lower limits.

For 28 sources, the SEDs are well described by a homogeneous HII region model (Mezger & Henderson, 1967; Yang et al., 2021). In this model, the electron density (n_e)

TABLE 5.5: Quantitative criteria of the physical parameters for HC HII regions, transition objects between the two stages, and UC HII regions from the literature.

Parameters	Diameter (pc)	n_e (cm^{-3})	EM (pc cm^{-6})
HC HII region	< 0.05	$> 10^5$	$> 10^8$
Transition objects	$0.05 - 0.1$	$10^4 - 10^5$	$10^7 - 10^8$
UC HII region	> 0.1	$< 10^4$	$< 10^7$

and physical diameter are treated as free parameters and are constrained by fitting the available radio continuum flux densities. The emission measure is then calculated from these quantities using $\text{EM} = n_e^2 \times \text{diam.}$

The remaining sources are optically thick across the observed frequency range and cannot be fully constrained by the homogeneous model. These sources were fitted using a single power law, and their derived physical properties should therefore be treated with caution. In particular, for sources that remain optically thick at 24 GHz, the observed flux density underestimates the true ionising output. Their electron densities, emission measures, and Lyman continuum photon fluxes are therefore treated as lower limits.

From the SED modelling, we derive electron densities, emission measures, diameters, turnover frequencies, and Lyman continuum photon fluxes. The turnover frequencies span ~ 4 – 15 GHz, with a mean value of ~ 9 GHz. The derived Lyman continuum fluxes are consistent with ionising sources ranging from early B-type to O-type stars. These physical parameters provide the basis for the classification described in the following subsection.

5.3.5 CLASSIFICATION OF COMPACT HII REGIONS

The derived physical parameters were used to classify the sources according to standard criteria for hypercompact (HC), ultracompact (UC), and transition objects. These classifications are based primarily on source size, electron density, and emission measure (Table 5.5).

Of the 35 sources, 20 satisfy the criteria for HC HII regions, exhibiting both small sizes (< 0.05 pc) and high electron densities ($> 10^5 \text{ cm}^{-3}$). A further three optically thick sources are also consistent with HC HII region properties when considering their lower-

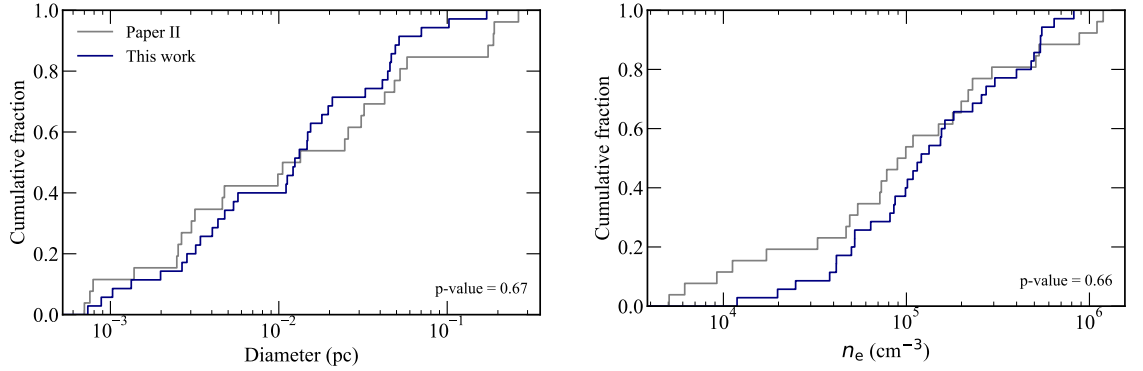


FIGURE 5.6: Cumulative distribution functions for diameter (left panel) and n_e (right panel) for the compact HII regions identified in Chapter 4 and in this chapter.

limit electron densities. Seven sources are classified as transitional objects, occupying the parameter space between HC and UC HII regions, while three sources are consistent with UC HII region properties. The remaining two sources show properties that overlap with those expected for thermal radio jets and are therefore treated as ambiguous jet-like candidates. These objects are considered separately in the Discussion.

5.4 THE COMPLETE SCOTCH SAMPLE

5.4.1 COMBINING THE SCOTCH I, II AND III SAMPLES

The results presented in this chapter complete the SCOTCH survey, extending the methodology developed in Chapters 3 and 4 to the fourth Galactic quadrant. By applying an identical observational strategy, source selection criteria, and analysis framework, the datasets from all three chapters form a homogeneous and directly comparable sample of compact HII regions associated with methanol masers.

The individual components of this sample have been described in detail in the preceding chapters. In particular, the identification of compact radio sources, the use of spectral indices to distinguish optically thick emission, and the modelling of radio SEDs to derive physical properties have all been carried out using consistent methods. This includes the treatment of optically thick sources as lower limits, the use of compactness criteria (e.g., y -factor constraints) to minimise spatial filtering effects, and the exclusion

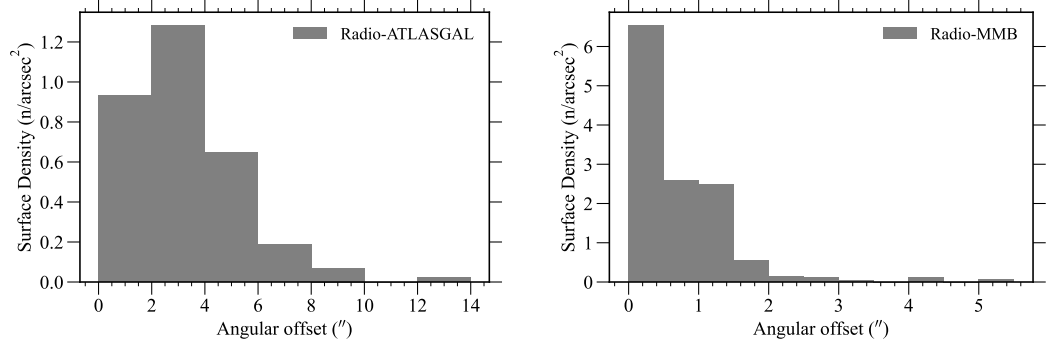


FIGURE 5.7: Histograms of the angular separation between the detected radio sources and their nearest ATLASGAL dust clump (left panel) and MMB maser (right panel). The histograms are binned using a value of 2 arcsec and 0.5 arcsec, respectively.

of extended or over-resolved sources identified in the high-resolution data.

To ensure the comparability of the Chapter 4 and Chapter 5 samples, we focus on two key physical properties: diameter and electron density. The cumulative distribution functions for these parameters are shown in Figure 5.6, and show strong agreement between the two samples. A two-sample KS test was performed to determine whether the electron densities and diameters are drawn from the same parent population. The test returned p -values of 0.67 for diameter and 0.66 for n_e , indicating no statistically significant difference between the two samples. This consistency suggests that the two datasets can be reliably combined for further analysis. Since the emission measure depends on both electron density and diameter, it is also expected to show broad consistency across the two samples.

Combining the 26 compact HII regions from Chapter 4 with the 35 newly identified HII regions from this chapter gives a unified sample of 61 HII regions. This combined sample consists of 34 HC HII regions, 15 transition objects, 9 UC HII regions, and 3 radio jet candidates. Notably, 11 sources remain optically thick at 24 GHz, suggesting that these are likely among the youngest objects in the sample, as their high optical depths indicate that they are still deeply embedded within their natal environments and have not yet expanded significantly. This combined dataset will be referred to as the SCOTCH sample throughout the remainder of this chapter.

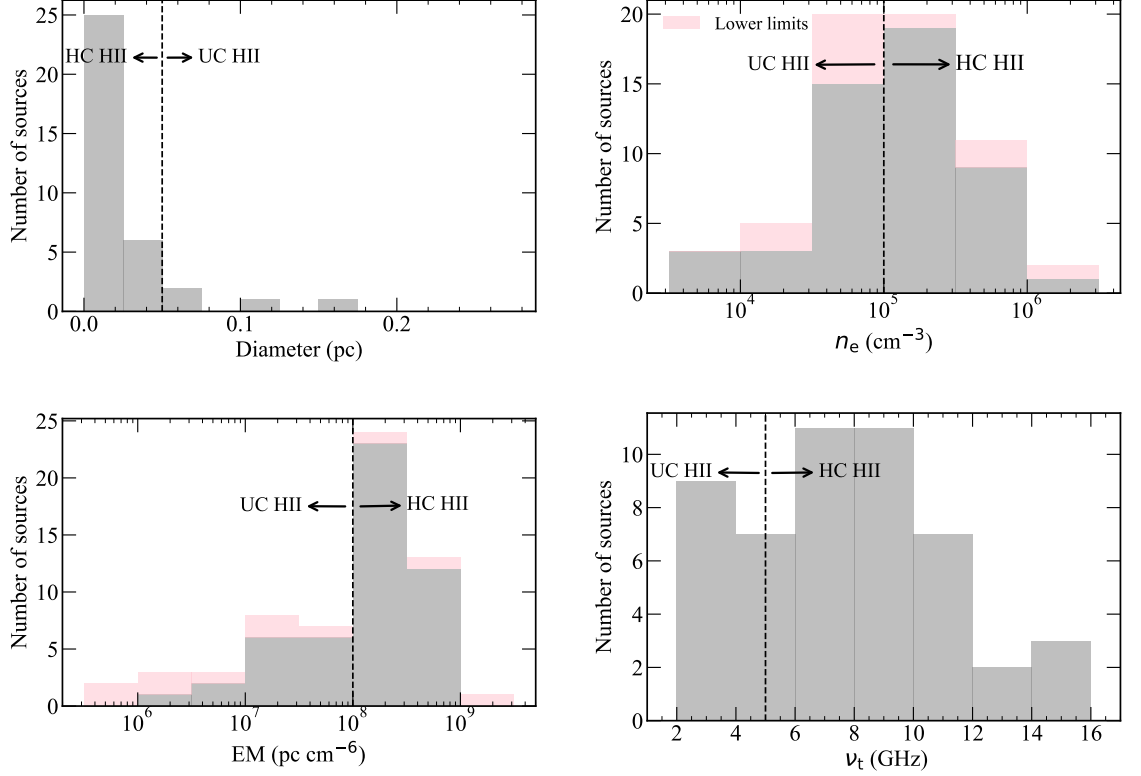


FIGURE 5.8: Histograms presenting the distribution of source parameters for the full sample of SCOTCH HII regions. The diameter (top-left panel), electron density (n_e ; top-right panel), emission measure (bottom-left panel) and turnover frequency (ν_t ; bottom-right panel) are shown. All histograms include all 61 HII regions identified except for the turnover-frequency plot, which excludes optically thick regions. The pink fraction of the distribution represents values that are lower limits. The bin sizes are 0.025 pc, 0.5 dex, 0.5 dex and 2 GHz for the diameter, n_e , emission measure and turnover frequency, respectively. The black vertical line and arrows emphasise the region of parameter space in which we expect to find HC HII regions.

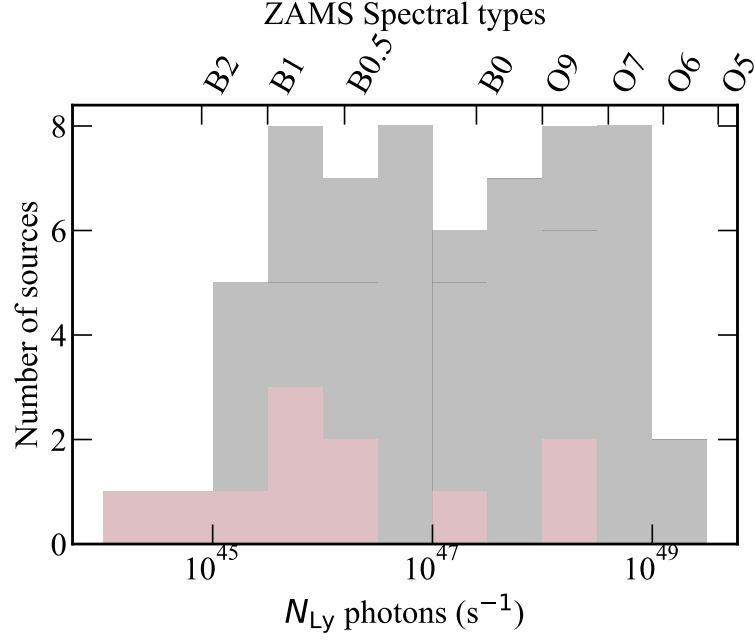


FIGURE 5.9: Histogram of the Lyman continuum photon flux for the HII regions identified throughout SCOTCH. The bin size is 0.5 dex. The pink fraction of the distribution represents values that are lower limits.

5.4.2 PHYSICAL PROPERTIES OF THE FULL SCOTCH SAMPLE

With the combined SCOTCH sample established, we now examine its global physical properties. The distributions of diameter, electron density, emission measure, turnover frequency, and Lyman-continuum photon flux are shown in Figures 5.8 and 5.9.

The majority of sources occupy the region of parameter space associated with HC HII regions, characterised by small sizes (<0.05 pc), high electron densities ($>10^5 \text{ cm}^{-3}$), and large emission measures ($>10^8 \text{ pc cm}^{-6}$). A significant fraction of sources remain optically thick at 24 GHz, indicating that their derived physical properties represent lower limits and that these objects are likely among the youngest in the sample.

The inclusion of the fourth-quadrant sources extends the parameter space probed by SCOTCH, particularly towards lower Lyman-continuum fluxes and smaller physical sizes. This confirms that the methanol maser selection technique is sensitive not only to the most luminous compact HII regions, but also to those associated with lower-luminosity high-mass stars.

A continuous distribution of physical properties is observed, spanning HC HII, transition, and UC HII regimes. This supports the interpretation that these classifica-

tions represent an evolutionary sequence rather than discrete populations. However, observational effects, including spatial filtering, sensitivity limits, and optical depth, must be considered when interpreting this distribution, particularly for sources that remain optically thick or are partially resolved.

Overall, the combined SCOTCH sample provides a statistically robust framework for investigating the earliest stages of HII region evolution. In the following section, we place these results in the context of previous studies and explore their implications for the evolution of compact ionised regions.

5.5 DISCUSSION

The complete SCOTCH sample provides a uniformly selected population of compact HII regions associated with methanol masers. By combining the fourth-quadrant sources presented in this chapter with those identified in Chapters 3 and 4, it is now possible to examine the properties of a large and homogeneous sample of young ionised regions in the context of the wider HCHII, UCHII, and compact HII region populations. In this section, the SCOTCH sample is compared with previous studies, the evolutionary implications of the observed physical properties are discussed, and the possibility of contamination from thermal radio jets is considered.

5.5.1 COMPARISON WITH KNOWN HC, UC AND COMPACT HII REGIONS

The final SCOTCH sample consists of 34 HCHII regions, 15 transition objects, 9 UCHII regions, and 3 jet-like candidates. Figure 5.10 shows the distribution of these sources in electron density–diameter space, compared with previously identified HCHII and transition objects from Yang et al. (2019); Yang et al. (2021), UCHII regions from Kalcheva et al. (2018), and compact HII regions from Khan et al. (2024).

The sources identified by SCOTCH occupy the same broad region of parameter space as previously known HCHII and transition objects, supporting their interpreta-

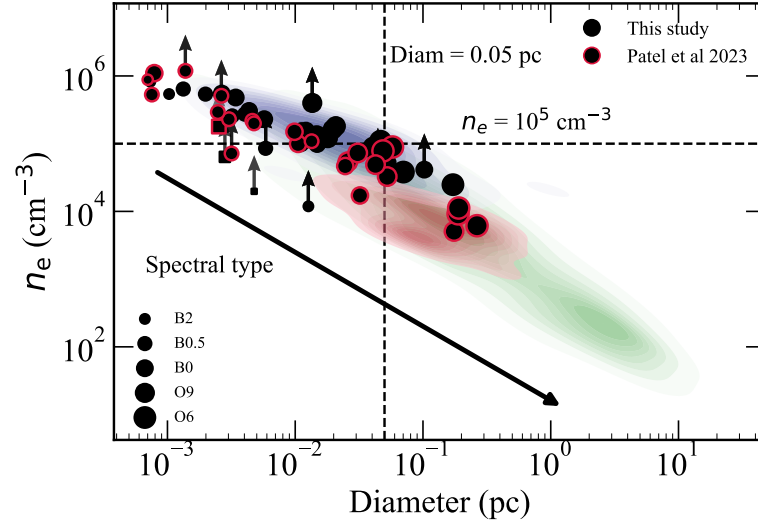


FIGURE 5.10: Distribution of the electron density as a function of diameter for the 61 objects identified in SCOTCH. The size of the data points denote the approximate ZAMS spectral type. The square data points represent the jet-like candidates. For the optically thick sources the entries for electron density and spectral type are lower limits. The blue coloured area represents a kernel density estimation for the previously identified HC HII and transition HII regions (Yang et al., 2019; Yang et al., 2021). The area coloured in pink represents the UC HII regions identified in Kalcheva et al. (2018), while the green area represents the compact regions in Khan et al. (2024). The black solid arrow shows the typical evolutionary trend a compact HII region is likely to follow as these objects expand.

tion as young compact ionised regions. However, the new sample extends the known population towards smaller diameters and, in several cases, lower Lyman-continuum photon fluxes. This likely reflects the methanol-maser-based selection strategy, which is particularly sensitive to deeply embedded high-mass protostars before they develop bright or spatially extended radio emission.

Only limited overlap is observed with the UC HII region population identified by Kalcheva et al. (2018). This is expected, since the survey was specifically designed to identify compact and optically thick sources rather than more evolved and extended HII regions. Most objects instead occupy the region of parameter space associated with HC HII and transition objects, indicating that the observations preferentially probe the earliest stages of compact HII region evolution.

One of the most significant features of Fig. 5.10 is the continuous distribution linking HC HII, transition, UC HII, and compact HII regions. The observed sources do not separate into clearly distinct populations, but instead form a smooth sequence in which electron density decreases as physical diameter increases. This behaviour

strongly suggests that these observational classes do not represent fundamentally different physical phenomena, but rather different stages within a continuous evolutionary process driven primarily by the expansion of ionised gas into the surrounding molecular environment.

The enlarged sample presented here therefore provides important evidence that HC HII regions are not rare or unusual objects, but instead represent the youngest observable stages of a broader compact HII region evolutionary sequence. Expanding the known HC HII region population also allows the underlying trends between size, density, and ionising luminosity to be examined more robustly than was previously possible from the relatively small samples available in earlier studies.

5.5.2 EVOLUTIONARY IMPLICATIONS

To investigate the evolutionary behaviour of compact HII regions, Fig. 5.11 compares Lyman-continuum photon flux with physical diameter for the SCOTCH sample and literature populations of HC HII, UC HII, and compact HII regions. In this parameter space, source diameter traces the expansion of the ionised region, while N_{Ly} provides an estimate of the ionising output of the embedded massive star.

A clear trend is observed in which larger HII regions are generally associated with higher Lyman-continuum photon fluxes, consistent with previous studies of compact ionised regions. However, the overall range of N_{Ly} values remains broadly similar across the HC HII, UC HII, and compact HII region populations, spanning approximately 10^{46} – 10^{49} s^{-1} . This suggests that the ionising luminosity of the central star is largely established by the HC HII region stage, while subsequent evolution is dominated primarily by the expansion and dilution of the ionised gas rather than by major increases in stellar ionising output.

The direction of evolution is therefore expected to proceed from small, dense HC HII regions towards larger and lower-density UC and compact HII regions, as indicated by the arrows in Figs. 5.10 and 5.11. As the ionised region expands, both the electron density and surface brightness decrease. This naturally produces the continuous distribution observed between the HC HII, transition, and UC HII regimes and

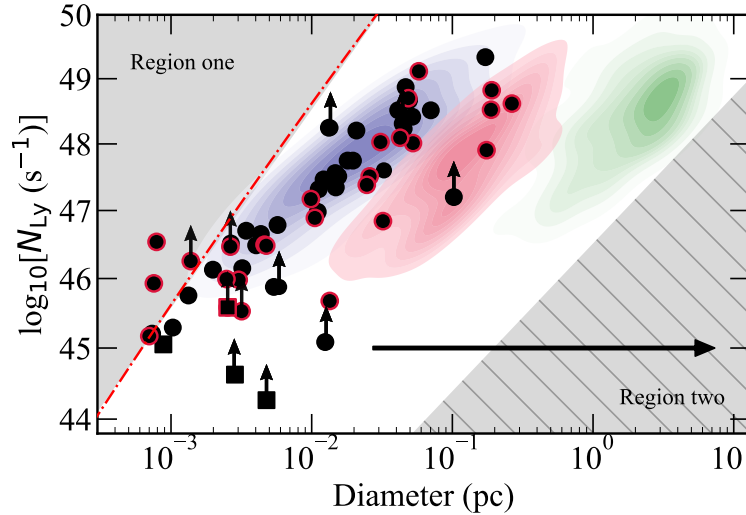


FIGURE 5.11: Distribution of the Lyman continuum flux as a function of diameter for the 61 objects identified in SCOTCH. The square data points represent the jet-like candidates. The coloured areas are as described in Fig. 5.10. The black arrow represents the implied evolutionary trend for HII regions. The red dot-dashed line represents the Strömgren expansion of HII regions, assuming a constant electron density of 10^6 cm^{-3} and a recombination coefficient $\alpha = 2.7 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$.

explains why the boundaries between these observational classes are not sharply defined.

Importantly, the results presented here suggest that HC HII and UC HII regions are not fundamentally distinct physical classes. Instead, they appear to represent different stages within a continuous evolutionary sequence governed primarily by the expansion of ionised gas into the surrounding molecular material. In this framework, the distinction between HC HII and UC HII regions remains observationally useful because HC HII regions still identify the youngest, densest, and most deeply embedded sources. However, the underlying physical picture appears continuous rather than discrete.

The distribution in Fig. 5.11 also shows that not all regions of parameter space are equally populated. There is a relative lack of very small sources with high Lyman-continuum photon fluxes. This is likely because HII regions surrounding O-type stars expand rapidly due to their strong ionising output, making the earliest hypercompact phase short-lived and therefore difficult to observe. Conversely, there is also a lack of large HII regions associated with low Lyman-continuum photon fluxes. This is likely a sensitivity effect: as lower-luminosity HII regions expand, their surface brightness falls below the detection limits of high-resolution radio observations.

Together, these effects produce the diagonal distribution observed across the HC HII, UC HII, and compact HII region populations. The SCOTCH survey extends this trend towards smaller physical sizes and lower ionising luminosities, demonstrating that high-frequency observations targeted towards methanol masers can recover compact ionised regions that are often missed by lower-frequency or lower-resolution surveys.

The enlarged HC HII region population identified here also has broader implications for our understanding of high-mass star formation. The results demonstrate that compact optically thick ionised regions are not restricted to the most luminous O-type stars, but are also associated with less luminous early B-type objects. This suggests that the formation of compact ionised regions is a common phase of massive star formation rather than a rare phenomenon associated only with extreme sources.

In addition, the large number of compact and optically thick sources identified by SCOTCH indicates that ionisation begins while the massive protostar is still deeply embedded within its natal environment. This supports evolutionary models in which accretion, ionisation, and feedback coexist during the earliest stages of massive star formation, rather than ionisation immediately dispersing the surrounding molecular material.

5.5.3 JET CONTAMINATION AND AMBIGUOUS SOURCES

A potential complication in identifying young compact HII regions is contamination from thermal radio jets. Both compact HII regions and ionised jets can produce free-free radio emission, and their spectral indices can overlap. Thermal radio jets typically have spectral indices in the range $-0.1 \leq \alpha \leq 1.6$ (Purser et al., 2016), which is similar to the values expected for partially optically thick compact HII regions. It is therefore important to consider whether some sources may instead be dominated by jet emission.

One way to distinguish between these possibilities is to compare the Lyman-continuum photon flux with bolometric luminosity. Photoionised HII regions are expected to lie close to the OB ZAMS relation, while radio jets typically have lower radio luminosities for a given bolometric luminosity. This comparison is shown in Fig. 5.12.

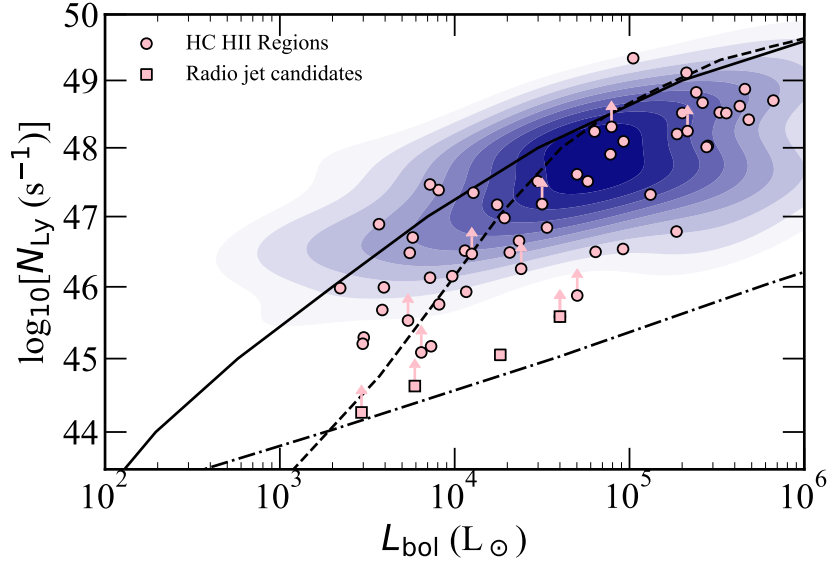


FIGURE 5.12: Lyman continuum photon flux vs. bolometric luminosity for the entire HII region sample. Blue contours highlight previously identified UC and HC HII regions, while pink squares indicate radio-jet candidates, with optically thick jets represented as upper limits. The dashed line illustrates the relationship for OB ZAMS star models (Martins et al., 2005; Davies et al., 2011), and the dot-dashed line represents a fit to radio jets found in Purser et al. (2016) and Purser et al. (2021). The solid black line corresponds to the Lyman continuum flux expected from a blackbody with the same radius and temperature as a ZAMS star (see Sánchez-Monge et al. 2013b for more detail).

Most sources lie close to the expected OB-star relation and overlap with previously identified HC HII and UC HII regions, supporting their interpretation as photoionised compact HII regions. The scatter around the ZAMS relation is expected because the observed radio-derived N_{Ly} values can be affected by dust absorption, optical depth, source geometry, and the presence of multiple ionising stars. In particular, compact embedded HII regions may absorb a significant fraction of ionising photons in dust before they contribute to the observed free-free emission (Wood & Churchwell, 1989a; Yang et al., 2021). As a result, the measured N_{Ly} values should generally be treated as lower limits.

A small number of sources lie close to the empirical radio-jet relation and are therefore treated as ambiguous jet-like candidates rather than secure compact HII regions. Two sources from the fourth-quadrant sample, G352.623–1.076 and G352.630–1.067, are particularly uncertain because they occupy the region where the HII region and jet relations converge. Both remain optically thick, meaning that their Lyman-continuum photon fluxes are likely underestimated. Their true positions in

Fig. 5.12 may therefore shift upwards with higher-frequency observations, potentially bringing them into better agreement with the compact HII region population.

G352.630–1.067 is especially notable because Chen et al. (2019) report a close spatial association between the radio source and a 6.7 GHz methanol maser. The maser emission is distributed in a linear structure oriented from south-west to north-east, which may indicate an ordered structure such as a disc, outflow, or jet. This makes the source difficult to classify using radio continuum data alone.

A similar ambiguity was discussed in Chapter 4 for G339.884–1.259. Although this source satisfies the physical criteria for an HC HII region, it is associated with outflow activity and possible jet emission. It is therefore retained within the HC HII region sample, but its interpretation remains uncertain. This highlights an important limitation of using radio continuum properties alone: in the youngest high-mass protostellar objects, ionised jets and compact HII regions may coexist or overlap spatially.

Overall, jet contamination does not dominate the SCOTCH sample. The majority of the detected sources have compact morphologies, physical properties, and Lyman-continuum fluxes consistent with photoionised HC HII or UC HII regions. However, the small number of ambiguous objects demonstrates the need for additional diagnostics, such as higher-frequency radio continuum observations, radio recombination lines, molecular outflow tracers, and higher-resolution imaging, to distinguish between ionised jets and the youngest compact HII regions.

5.6 CONCLUSIONS

In this chapter, we have presented the final stage of the SCOTCH survey: a high-frequency radio continuum search for compact HII regions associated with MMB methanol masers in the fourth Galactic quadrant. Low-resolution ATCA observations were obtained towards 335 fields, followed by high-resolution observations of compact and optically thick candidates. This completes the observational strategy developed in Chapters 3 and 4, providing a consistently selected sample of compact ionised regions

across the southern Galactic plane.

Radio continuum emission was detected towards 116 of the 335 low-resolution fields, corresponding to a detection rate of approximately 30 per cent. From these detections, 43 compact or optically thick radio sources were selected for high-resolution follow-up. The high-resolution observations confirmed 35 compact radio sources suitable for further physical analysis. Radio SED modelling was then used to derive source diameters, electron densities, emission measures, turnover frequencies, and Lyman-continuum photon fluxes.

Based on their derived physical properties, the fourth-quadrant sample contains 23 HC HII regions, 7 transition objects, 3 UC HII regions, and 2 ambiguous jet-like candidates. Combining these sources with those identified in Chapter 4 gives a complete SCOTCH sample of 61 compact HII regions, consisting of 34 HC HII regions, 15 transition objects, 9 UC HII regions, and 3 jet-like candidates. Eleven sources remain optically thick at 24 GHz, indicating that they are likely among the youngest and most deeply embedded objects in the sample.

The SCOTCH sample is strongly associated with methanol masers and dense ATLASGAL clumps, confirming that these compact radio sources trace very young high-mass star-forming environments. The derived physical properties show that many of the HC HII regions identified here are smaller, denser, and associated with lower Lyman-continuum photon fluxes than many previously known examples. This demonstrates that methanol-maser-selected, high-frequency radio observations are particularly effective at identifying compact ionised regions around lower-luminosity high-mass stars.

Comparison with literature samples of HC HII, UC HII, and compact HII regions shows that the SCOTCH sources form part of a continuous evolutionary sequence. The electron density decreases as source diameter increases, supporting the interpretation that HC HII, transition, UC HII, and compact HII regions are not sharply distinct classes, but represent different stages in the expansion of ionised gas around young massive stars. The distribution of Lyman-continuum photon flux with diameter further suggests that the ionising output of the central star is largely established by the HC HII

region stage, with subsequent evolution dominated by expansion and decreasing surface brightness.

A small number of sources have properties that overlap with those expected for thermal radio jets. These objects are treated as ambiguous rather than confident HII regions. However, the majority of the SCOTCH sample has compact morphology, physical properties, and Lyman-continuum fluxes consistent with photoionised HC or UC HII regions. Future higher-frequency radio observations, radio recombination line studies, and molecular outflow tracers will be required to confirm the nature of the most ambiguous sources.

Overall, the SCOTCH survey has significantly increased the number of known HC HII regions and extended the population towards smaller sizes and lower ionising luminosities. This provides a more complete view of the earliest observable stages of compact HII region evolution and demonstrates the effectiveness of combining methanol maser selection with high-frequency, high-resolution radio continuum observations.

CHAPTER 6

SUMMARY AND CONCLUSIONS

This thesis has presented the SCOTCH survey: a systematic high-frequency radio continuum search for hypercompact (HC) HII regions associated with 6.7 GHz Class II methanol masers. Using targeted Australia Telescope Compact Array (ATCA) observations at 18 and 24 GHz, this work has identified and characterised one of the largest homogeneous samples of compact ionised regions associated with the earliest stages of high-mass star formation.

The primary motivation for this project was to improve our understanding of the earliest observable ionised phase of massive stellar evolution. Although HC HII regions are thought to represent a critical stage between the deeply embedded protostellar phase and the development of larger ultracompact (UC) HII regions, relatively few examples were known prior to this work. This was largely due to observational limitations. HC HII regions are extremely compact, dense, and often optically thick at commonly used radio frequencies such as 5 GHz, making them difficult to detect in large-scale Galactic plane surveys.

To overcome this limitation, the SCOTCH survey adopted a targeted obser-

vational strategy based on methanol masers. Since Class II methanol masers are exclusively associated with the early stages of high-mass star formation, they provide an efficient method for identifying deeply embedded young massive stars likely to host compact ionised regions. By combining methanol maser selection with sensitive high-frequency radio continuum observations, this thesis has significantly expanded the known population of HC HII regions and provided new insight into their role within the broader evolutionary sequence of massive star formation.

This chapter summarises the major results of the thesis, discusses their implications for our understanding of compact HII region evolution, and outlines future directions for observational follow-up.

6.1 OVERVIEW OF THE SCOTCH SURVEY

The SCOTCH survey targeted methanol masers identified by the Methanol Multibeam (MMB) survey across the southern Galactic plane. The project was carried out in multiple stages, combining low-resolution observations designed to identify candidate compact radio sources with high-resolution follow-up observations aimed at constraining their physical properties.

Low-resolution ATCA observations at 18 and 24 GHz were used to identify compact radio continuum emission associated with methanol masers and dense dust clumps traced by ATLASGAL. Candidate HC HII regions were selected using a combination of compact morphology, spatial coincidence with embedded star-forming tracers, and rising radio spectral indices indicative of optically thick free-free emission.

High-resolution follow-up observations were then obtained for the most promising candidates. These observations allowed accurate measurements of source sizes and flux densities, enabling radio spectral energy distributions (SEDs) to be modelled and physical parameters such as electron density, emission measure, turnover frequency, and Lyman-continuum photon flux to be derived.

Across the full SCOTCH survey, compact radio emission was detected towards

a large fraction of methanol maser sites, confirming the strong relationship between methanol masers and deeply embedded ionising sources. The final combined SCOTCH sample consists of:

- 34 HC HII regions,
- 15 transition objects,
- 9 UC HII regions,
- and 3 jet-like candidates.

Several of these sources remain optically thick even at 24 GHz, indicating that they are among the youngest and densest ionised regions currently known.

6.2 THE NATURE OF HC HII REGIONS

One of the primary goals of this thesis was to determine whether HC HII regions represent a genuinely distinct class of object or simply the youngest observable stage in the evolution of compact ionised regions.

The SCOTCH results strongly support the latter interpretation.

The derived physical properties show a continuous distribution in diameter, electron density, emission measure, turnover frequency, and Lyman-continuum photon flux. Rather than separating into distinct populations, the HC HII, transition, and UC HII regions identified throughout this thesis form a smooth sequence in parameter space. Electron density decreases systematically as source diameter increases, while optical depth and emission measure similarly evolve in a gradual manner.

This continuity suggests that HC HII and UC HII regions are not fundamentally different physical phenomena. Instead, they appear to represent different stages in the expansion of ionised gas around newly formed massive stars.

The results presented here therefore support an evolutionary picture in which newly formed massive stars first produce extremely compact, dense, and optically thick

ionised regions. As the ionised gas expands into the surrounding environment, the source diameter increases while the electron density and optical depth decrease, naturally producing the transition from HC HII to UC HII and eventually larger compact HII regions.

In this framework, the traditional distinction between HC HII and UC HII regions remains observationally useful, since HC HII regions still identify the youngest, densest, and most embedded sources. However, the SCOTCH results suggest that these classifications should not necessarily be interpreted as fundamentally separate physical classes. Instead, they are better understood as convenient observational descriptions within a continuous evolutionary sequence.

This represents one of the key conclusions of the thesis.

6.3 IMPLICATIONS FOR HIGH-MASS STAR FORMATION

The enlarged HC HII region population identified by SCOTCH provides important insight into the earliest stages of high-mass star formation.

Prior to studies such as SCOTCH, the known HC HII region population was relatively small and dominated by luminous sources associated with O-type stars. As a result, it remained unclear whether HC HII regions represented a rare or unusual phase of evolution, or whether they were simply difficult to detect observationally.

The SCOTCH survey demonstrates that compact optically thick ionised regions are considerably more common than previously recognised. Furthermore, these regions are not restricted to the most luminous massive stars. Many SCOTCH sources are associated with lower Lyman-continuum photon fluxes consistent with early B-type stars, extending the known HC HII population towards lower luminosities and smaller physical sizes.

This has several important implications.

First, it suggests that the formation of compact ionised regions is a common outcome of massive star formation rather than a rare phenomenon associated only

with extreme objects. Second, the existence of deeply embedded optically thick sources indicates that ionisation begins very early in the evolution of massive protostars, while substantial dense material is still present in the surrounding environment.

This is particularly important because one of the longstanding problems in massive star formation is understanding how accretion can continue despite the strong radiative feedback produced by the forming star. The SCOTCH results provide observational evidence that compact ionised structures can coexist with deeply embedded environments, implying that ionisation does not immediately halt accretion or rapidly disperse the natal material.

The presence of sources that remain optically thick even at 24 GHz further suggests that some compact HII regions may remain confined for significant periods of time, potentially due to high surrounding densities, ongoing accretion flows, or pressure confinement within dense molecular clumps.

Overall, the SCOTCH survey supports a picture in which the onset of ionising feedback occurs gradually and while the massive protostar is still actively embedded within its natal environment.

6.4 THE ROLE OF METHANOL MASERS

This thesis has also demonstrated the effectiveness of methanol masers as tracers of the earliest ionised stages of massive star formation.

By targeting Class II methanol masers, the SCOTCH survey was able to identify a population of compact ionised regions that are likely underrepresented in traditional lower-frequency radio continuum surveys. The strong association between methanol masers, dense ATLASGAL dust clumps, and compact radio continuum emission confirms that methanol masers preferentially trace deeply embedded high-mass star-forming regions near the onset of ionisation.

Importantly, the survey demonstrates that high-frequency radio observations targeted towards methanol masers provide a highly efficient method for identifying

young compact HII regions, including sources that may remain undetected at lower radio frequencies due to optical depth effects.

This strategy has therefore proven to be an effective approach for probing the earliest observable ionised phase of massive star formation.

6.5 LIMITATIONS AND AMBIGUITIES

Although the SCOTCH survey has substantially improved the known population of HC HII regions, several limitations remain.

A small number of sources exhibit properties consistent with thermal radio jets rather than photoionised HII regions. In the youngest massive protostars, these two phenomena may coexist, making classification difficult using radio continuum observations alone. In particular, optically thick free-free emission can arise from both ionised jets and compact HII regions, leading to ambiguities in spectral index and radio luminosity measurements.

In addition, several SCOTCH sources remain optically thick at the highest observed frequencies. For these objects, the derived electron densities, emission measures, and Lyman-continuum photon fluxes represent lower limits rather than fully constrained measurements.

Future higher-frequency observations will therefore be required to determine the true turnover frequencies and physical properties of the youngest sources in the sample.

6.6 FUTURE WORK

The SCOTCH survey provides a strong foundation for future observational studies of compact ionised regions and massive star formation.

The most immediate priority is follow-up observations of the optically thick sources identified in this thesis. Observations at frequencies above 24 GHz will al-

low these sources to be observed in the optically thin regime, enabling more accurate measurements of their electron densities, emission measures, and ionising fluxes.

Higher-angular-resolution radio observations will also help distinguish between compact HII regions and ionised jets, particularly for the ambiguous jet-like candidates identified in this thesis. Radio recombination line observations could further constrain the kinematics and physical structure of the ionised gas.

In addition, molecular line observations with facilities such as ALMA will provide important information on the surrounding dense gas, including evidence for accretion flows, rotation, fragmentation, and molecular outflows. Such observations will help clarify the relationship between compact ionised regions and the larger-scale protostellar environment.

Finally, extending the SCOTCH observational strategy to the remaining northern MMB methanol masers would allow the construction of a near-complete Galactic census of HC HII regions. Such a sample would provide substantially improved constraints on the lifetimes, luminosity distribution, and evolutionary behaviour of compact ionised regions across the Galaxy.

6.7 FINAL REMARKS

This thesis has presented one of the largest systematic searches for HC HII regions conducted to date. Through the combination of methanol maser selection, high-frequency radio continuum observations, and high-resolution follow-up imaging, the SCOTCH survey has significantly expanded the known population of compact ionised regions associated with the earliest stages of massive star formation.

The results demonstrate that HC HII regions are not isolated or unusual objects, but instead form part of a continuous evolutionary sequence linking deeply embedded massive protostars with larger UC and compact HII regions. The enlarged SCOTCH sample shows that compact ionised regions span a broad range of luminosities and physical properties, indicating that the onset of ionisation is a common and important

phase in the evolution of massive stars.

More broadly, this work provides new observational evidence that ionising feedback begins while massive stars remain deeply embedded within their natal environments, supporting evolutionary models in which accretion, ionisation, and feedback coexist during the earliest stages of high-mass star formation.

The SCOTCH survey therefore provides an important step towards a more complete observational understanding of how massive stars form and evolve during their earliest ionised phases.

CHAPTER 7

APPENDIX

7.1 CHAPTER 3

The following table lists the full observational field parameters from Chapter 3.

TABLE 7.1: Observational field parameters from all observed fields. The field names and pointing centres of the observations are based on the MMB names and positions.

Field name	RA	Dec.	Field		Beam size	
	(J2000)	(J2000)	rms	Major	Minor	Position angle
	(h:m:s)	(d:m:s)	(mJy)	(arcsec)	(arcsec)	(°)
G002.143+00.009	17:50:36.0	−27:05:47	0.49	11	6.7	72
G002.521−00.220	17:52:50.0	−27:05:26	0.31	11	6.7	72
G002.536+00.198	17:50:46.5	−26:39:50	0.31	11	6.7	71
G002.591−00.029	17:51:42.5	−26:44:33	0.35	11	6.7	71

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Table 7.1 – continued from previous page

Field name	RA	Dec.	Field		Beam size		
	(J2000)	(J2000)	rms	Major	Minor	Position angle	
	(h:m:s)	(d:m:s)	(mJy)	(arcsec)	(arcsec)	(°)	
G002.615+00.134	17:51:12.2	−26:37:40	21	12	6.7	71	
G002.703+00.040	17:51:46.5	−26:36:23	0.33	12	6.6	71	
G003.253+00.018	17:53:06.3	−26:08:29	0.78	11	6.6	72	
G003.312−00.399	17:54:50.7	−26:18:23	0.39	11	6.6	72	
G003.442−00.348	17:54:55.7	−26:09:50	9.3	11	6.6	72	
G003.502−00.200	17:53:38.5	−26:55:53	0.39	11	6.6	72	
G003.910+00.001	17:54:38.9	−25:34:50	9.1	11	6.6	73	
G004.393+00.079	17:55:21.4	−25:07:04	1.8	11	6.6	73	
G004.434+00.129	17:55:19.1	−25:04:44	4.8	11	6.6	74	
G004.569−00.079	17:56:30.5	−25:03:52	0.39	11	6.6	74	
G004.586+00.028	17:56:34.3	−24:23:59	0.28	11	6.6	75	
G004.676+00.276	17:55:18.8	−24:46:30	0.92	11	6.7	75	
G004.866−00.171	17:57:17.5	−24:48:41	0.28	11	6.7	75	
G005.618−00.082	17:58:26.4	−24:12:26	0.3	11	6.7	75	
G005.630−00.294	17:59:34.3	−24:14:22	0.58	11	6.7	76	
G005.657+00.416	17:56:56.4	−23:51:36	0.29	11	6.7	77	
G005.677−00.027	17:58:38.7	−24:02:41	0.35	11	6.8	76	
G005.885−00.393	18:00:30.4	−24:04:01	430	11	6.8	76	
G005.900−00.430	18:00:36.5	−24:03:52	27	11	6.8	76	
G010.629−00.333	18:10:19.1	−19:54:10	3.6	11	6.9	89	
G011.936−00.150	18:12:16.3	−18:41:25	0.38	11	6.9	89	
G011.936−00.616	18:14:01.0	−18:53:23	20	10	6.6	70	
G011.992−00.272	18:12:49.9	−18:39:46	0.42	9.9	6.6	71	
G012.025−00.031	18:11:23.2	−18:52:22	0.42	9.9	6.5	72	
G012.112−00.126	18:12:31.2	−18:30:45	0.14	11	6.8	90	

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Table 7.1 – continued from previous page

Field name	RA	Dec.	Field		Beam size		
	(J2000)	(J2000)	rms	Major	Minor	Position angle	
	(h:m:s)	(d:m:s)	(mJy)	(arcsec)	(arcsec)	(°)	
G012.181−00.123	18:12:38.8	−18:23:29	3.7	9.9	6.6	72	
G012.199−00.033	18:12:23.6	−18:22:53	1.6	10	6.6	72	
G012.202−00.120	18:12:37.9	−18:24:51	6.6	11	6.9	89	
G012.265−00.051	18:12:42.2	−18:13:57	0.25	10	6.6	73	
G012.526+00.016	18:14:07.9	−17:04:48	0.21	9.9	6.7	74	
G012.625−00.017	18:13:11.6	−17:59:34	0.84	10	6.6	74	
G012.904−00.031	18:13:45.6	−17:47:22	0.27	9.9	6.7	74	
G013.179+00.061	18:14:01.8	−17:28:33	5	9.8	6.8	74	
G013.657−00.599	18:17:08.3	−17:39:30	0.35	9.9	6.8	74	
G013.696−00.156	18:15:50.6	−17:07:49	0.23	9.9	6.8	76	
G013.713−00.083	18:15:36.2	−17:04:29	0.57	10	6.8	76	
G014.101+00.087	18:15:44.8	−16:38:49	3.4	10	6.8	75	
G014.230−00.509	18:18:13.9	−16:49:48	0.3	10	6.8	75	
G014.390−00.020	18:16:43.9	−16:26:53	2.3	10	6.9	77	
G014.457−00.143	18:17:17.2	−16:27:02	0.16	11	7	90	
G014.490+00.014	18:16:46.6	−16:20:28	6.3	10	6.9	77	
G014.521+00.155	18:16:20.1	−16:14:41	0.27	10	6.8	79	
G014.604+00.017	18:17:00.5	−16:14:40	0.77	11	7	−90	
G014.631−00.577	18:19:14.6	−16:29:31	0.3	10	6.8	79	
G014.991−00.121	18:18:16.7	−15:58:16	0.48	10	6.8	81	
G015.034−00.677	18:20:24.8	−16:11:32	110	10	6.8	81	
G015.094+00.192	18:17:26.5	−15:43:27	0.29	10	6.8	83	
G015.607−00.255	18:19:51.3	−15:30:32	0.3	10	6.8	83	
G018.460−00.004	18:24:36.2	−12:51:09	17	11	7.2	89	
G018.667+00.025	18:24:52.6	−12:39:20	0.3	11	7.1	−90	

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Table 7.1 – continued from previous page

Field name	RA	Dec.	Field		Beam size		
	(J2000)	(J2000)	rms	Major	Minor	Position angle	
	(h:m:s)	(d:m:s)	(mJy)	(arcsec)	(arcsec)	(°)	
G018.735−00.227	18:25:55.3	−12:43:35	0.27	11	7.1	−90	
G019.496+00.115	18:26:04.4	−11:52:32	4.4	11	7.2	90	
G019.612−00.134	18:27:17.2	−11:53:46	0.87	11	7.2	−90	
G312.698+00.126	14:14:00.7	−61:10:30	0.14	13	7.6	−79	
G316.381−00.379	14:42:33.0	−60:18:02	0.92	13	7.5	−82	
G320.424+00.089	15:09:37.1	−57:59:00	1.4	12	7.4	−84	
G326.476+00.695	15:43:16.6	−54:07:15	0.21	12	7.2	−87	
G327.402+00.445	15:49:19.1	−53:45:17	5.2	12	7.1	−88	
G329.556+00.181	16:01:29.0	−52:35:03	0.21	11	7.1	−88	
G331.059+00.375	16:08:04.6	−51:25:25	0.13	11	7.7	77	
G331.120−00.118	16:09:00.1	−52:06:02	0.17	11	7.6	78	
G331.132−00.244	16:10:59.3	−51:50:23	5.5	11	7.7	78	
G331.134+00.156	16:09:46.9	−51:33:28	0.38	11	7.7	78	
G331.278−00.188	16:11:27.0	−51:42:00	4.8	11	7.7	78	
G331.342−00.346	16:12:20.7	−51:46:05	2.3	11	7.7	78	
G331.425+00.264	16:10:06.5	−51:15:33	0.12	11	7.7	77	
G331.437−00.304	16:12:33.2	−51:53:55	0.13	11	7.7	78	
G331.442−00.187	16:12:12.7	−51:35:11	1.5	11	7.8	77	
G331.542−00.066	16:12:08.9	−51:25:47	14	11	7.7	77	
G331.543−00.066	16:12:08.5	−51:26:13	13	11	7.1	−88	
G331.556−00.121	16:12:27.3	−51:27:32	5.6	11	7.6	78	
G331.710+00.603	16:10:00.9	−50:48:52	0.13	11	7.6	72	
G331.900−01.186	16:18:49.0	−51:59:30	0.12	11	7.6	74	
G332.094−00.421	16:16:17.4	−51:15:39	1.1	11	7.6	74	
G332.295−00.094	16:15:44.9	−50:56:16	2.1	11	7.6	74	

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Table 7.1 – continued from previous page

Field name	RA	Dec.	Field		Beam size		
	(J2000)	(J2000)	rms	Major	Minor	Position angle	
	(h:m:s)	(d:m:s)	(mJy)	(arcsec)	(arcsec)	(°)	
G332.295+02.280	16:05:42.2	−49:11:27	0.16	11	7.5	76	
G332.296−00.094	16:15:44.9	−50:56:15	2.1	5.3	2.1	3.6	
G332.351−00.436	16:17:43.4	−51:06:51	0.16	11	7.5	75	
G332.352−00.117	16:16:54.6	−50:54:27	0.16	11	7.6	76	
G332.364+00.607	16:12:58.6	−50:23:11	0.14	11	7.6	75	
G332.560−00.148	16:17:04.5	−50:46:55	0.6	4.9	2.2	9.7	
G332.583+00.147	16:15:56.9	−50:33:33	0.14	11	7.6	75	
G332.604−00.168	16:17:29.1	−50:45:43	0.16	11	7.6	76	
G332.653−00.621	16:19:39.4	−51:03:22	4.2	11	7.6	75	
G332.701−00.588	16:19:51.9	−51:00:21	0.35	11	7.6	75	
G332.725−00.621	16:19:59.8	−50:59:44	0.39	11	7.6	75	
G332.726−00.621	16:19:13.6	−50:47:23	0.46	5.5	2.1	5.2	
G332.813−00.701	16:20:24.2	−51:06:16	0.21	11	7.6	75	
G332.826−00.549	16:20:11.0	−50:53:14	61	11	7.6	75	
G332.854+00.817	16:14:21.2	−49:53:13	0.15	11	7.5	76	
G332.942−00.686	16:21:22.4	−50:52:24	0.2	11	7.6	77	
G332.960+00.135	16:17:50.4	−50:18:17	0.15	11	7.5	76	
G332.963−00.679	16:21:18.1	−50:53:04	0.19	11	7.6	78	
G332.975+00.773	16:15:03.0	−49:50:30	3.1	11	7.6	77	
G332.987−00.487	16:20:37.7	−50:43:49	0.49	11	7.6	78	
G333.029−00.015	16:14:46.7	−50:06:21	0.15	11	7.6	77	
G333.029−00.063	16:18:56.8	−50:23:54	0.62	11	7.6	77	
G333.068−00.447	16:22:57.3	−50:39:15	1.3	11	7.6	78	
G333.109−00.500	16:21:13.3	−50:39:13	1.4	11	7.1	−89	
G333.121−00.434	16:21:00.7	−50:35:27	60	11	7.6	79	

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Table 7.1 – continued from previous page

Field name	RA	Dec.	Field		Beam size		
	(J2000)	(J2000)	rms	Major	Minor	Position angle	
	(h:m:s)	(d:m:s)	(mJy)	(arcsec)	(arcsec)	(°)	
G333.128−00.440	16:21:01.4	−50:35:22	61	12	7	−88	
G333.128−00.560	16:19:51.4	−50:52:05	0.22	11	7.7	79	
G333.130−00.560	16:19:25.9	−50:59:31	0.21	11	7.1	−90	
G333.163−00.101	16:19:42.6	−50:19:52	1.3	11	7.6	80	
G336.983−00.183	16:36:12.4	−47:37:58	1.1	11	7.6	78	
G336.994−00.027	16:35:32.3	−47:31:15	3.1	11	7.6	80	
G337.300−00.874	16:41:09.8	−47:51:20	0.12	12	6.9	−88	
G338.280+00.542	16:38:16.7	−46:12:18	0.37	6.6	2	5.7	
G338.461−00.245	16:42:18.3	−46:34:18	0.38	6.4	2	5.7	
G338.472+00.289	16:40:03.1	−46:11:43	0.18	6.6	2	5.6	
G338.561+00.218	16:40:37.2	−46:11:15	0.17	6.6	2	6	
G338.566+00.110	16:41:07.7	−46:15:39	0.25	6.6	2	6	
G338.925+00.557	16:40:59.7	−45:41:57	1.2	6.7	2	6.3	
G338.926+00.634	16:40:15.4	−45:39:03	3.5	12	6.9	−86	
G339.294+00.139	16:43:39.9	−45:44:12	0.21	12	6.9	−87	
G339.582−00.127	16:46:39.4	−45:29:18	0.2	6.8	2	6.1	
G339.622−00.121	16:46:22.8	−45:38:06	0.36	6.8	2	6.3	
G339.682−01.207	16:51:09.1	−46:10:32	0.17	6.7	2	6.4	
G339.762+00.054	16:46:57.5	−45:09:57	0.17	6.8	2	7	
G339.884−01.259	16:52:09.7	−46:07:57	0.72	6.8	2	6.7	
G339.980−00.538	16:49:14.6	−45:36:32	0.89	12	6.9	−86	
G340.054−00.244	16:48:13.3	−45:21:33	3.5	7	2	7.3	
G340.543−00.162	16:49:30.7	−44:57:40	0.16	12	6.8	−86	
G340.785−00.096	16:50:14.8	−44:42:30	0.46	7.2	2	7.4	

TABLE 7.2: Extracted source parameters from our detected radio sources. Column 1 lists the radio name, derived from Galactic coordinates using IMFIT. Columns 2 and 3 provide the Right Ascension and Declination. Columns 4 to 7 contain the peak flux density, integrated flux density, and their respective errors. Columns 8 to 10 describe the source size in arcseconds.

Radio name	RA (J2000) (h:m:s)	Dec. (J2000) (d:m:s)	f_{peak} (mJy beam $^{-1}$)	Δf_{peak} (mJy beam $^{-1}$)	f_{int} (mJy)	Δf_{int} (mJy)	Major (arcsec)	Minor (arcsec)	PA ($^{\circ}$)
G002.143+0.009	17:50:36.0	-27:05:47	6.6	0.29	8.4	0.52	15	7.8	63
G002.614+0.134	17:51:12.2	-26:37:40	170	7.8	230	15	16	8.2	69
G003.307-0.403	17:54:50.5	-26:18:15	2.9	0.3	3.7	0.55	15	8	65
G003.438-0.349	17:54:55.7	-26:09:47	94	2.8	100	4.4	14	6.9	67
G003.910+0.001	17:54:38.8	-25:34:44	93	3.1	100	4.9	15	6.7	66
G004.680+0.277	17:55:18.8	-24:46:29	9.8	0.31	10	0.47	14	6.8	67
G005.629-0.291	17:59:33.8	-24:14:20	2.9	0.16	8	0.64	19	13	77
G005.885-0.392	18:00:30.4	-24:04:01	7900	230	8400	350	14	7.1	71
G010.629-0.338	18:10:19.1	-19:54:10	36	2.4	46	4.4	11	7.9	-90
G011.904-0.141	18:12:11.2	-18:41:29	77	2	47	4.1	14	7.3	-89
G011.937-0.616	18:14:01.1	-18:53:23	660	34	930	68	11	8.1	72
G012.112-0.127	18:12:33.4	-18:30:06	0.68	0.056	0.86	0.11	13	7	-76
G012.199-0.034	18:12:23.6	-18:22:53	39	2.8	46	4.8	11	6.9	71
G012.208-0.102	18:12:39.6	-18:24:21	240	9.5	270	16	11	7.4	86
G012.632-0.017	18:13:12.3	-17:59:32	5.6	0.71	16	3	15	12	65
G013.631-0.602	18:17:21.9	-17:23:39	3	0.15	4.1	0.29	12	7.7	80
G013.693-0.160	18:15:51.5	-17:07:45	1.9	0.12	2.2	0.2	11	7.2	74
G013.713-0.080	18:15:36.3	-17:04:27	2.7	0.25	14	3.5	24	15	35
G014.104+0.092	18:15:45.1	-16:38:51	31	4.8	50	11	14	7.7	78
G014.229-0.510	18:18:12.6	-16:49:26	1.5	0.34	2.7	0.95	15	7.9	75
G014.391-0.021	18:16:44.0	-16:26:59	11	2	40	13	19	13	37
G014.490+0.021	18:16:46.7	-16:20:34	37	2.8	150	19	18	15	42
G014.599+0.020	18:16:59.8	-16:14:49	6.5	0.12	8	0.4	11	8	-85
G014.610+0.012	18:17:02.7	-16:14:28	6.2	0.27	7	0.58	12	7.2	-87
G014.986-0.122	18:18:16.9	-15:58:23	4.7	0.51	7.9	1.3	14	8.7	-81
G018.461-0.004	18:24:36.3	-12:51:05	420	14	430	20	11	7.8	88
G018.665+0.029	18:24:52.6	-12:39:19	5.5	0.49	6	0.99	12	7.2	89

Table 7.2 – continued from previous page

Radio name	RA (J2000) (h:m:s)	Dec. (J2000) (d:m:s)	f_{peak} (mJy beam ⁻¹)	Δf_{peak} (mJy beam ⁻¹)	f_{int} (mJy)	Δf_{int} (mJy)	Major (arcsec)	Minor (arcsec)	PA (°)
G018.720−0.234	18:25:56.1	−12:43:46	1.8	0.058	3.5	0.39	13	12	−53
G018.735−0.227	18:25:56.3	−12:42:49	1.7	0.27	2.5	1	14	8.4	−80
G019.491+0.135	18:26:04.4	−11:52:33	89	3.7	130	12	12	9.4	−89
G316.363−0.362	14:43:12.7	−60:17:11	6.9	0.35	18	3.3	21	12	−82
G320.416+0.116	15:09:32.3	−57:59:19	10	0.8	15	1.8	15	9.1	−78
G320.427+0.103	15:09:39.7	−57:59:40	22	0.81	23	1.6	13	7.5	−87
G326.475+0.703	15:43:16.6	−54:07:14	3.1	0.3	4.1	0.56	12	8.6	−84
G327.402+0.445	15:49:19.3	−53:45:14	120	2.7	130	4	12	7.3	−87
G331.130−0.243	16:10:59.1	−51:50:25	140	17	310	53	20	9.1	50
G331.145+0.135	16:09:24.1	−51:33:08	11	0.55	22	1.5	15	11	49
G331.279−0.190	16:11:27.3	−51:42:00	55	6.2	300	55	31	15	−85
G331.334−0.335	16:12:21.3	−51:46:06	23	2.4	120	24	33	13	−76
G331.442−0.187	16:12:12.7	−51:35:11	69	1.3	71	1.9	11	7.8	76
G331.542−0.067	16:12:08.9	−51:25:47	330	46	370	74	12	8.2	71
G331.557−0.120	16:12:27.4	−51:27:31	150	12	360	40	16	13	60
G331.710+0.604	16:10:01.2	−50:49:29	1.5	0.12	1.9	0.28	13	8.4	61
G332.098−0.419	16:16:17.2	−51:18:07	17	2.1	40	11	16	13	81
G332.290−0.091	16:15:43.4	−50:56:58	20	—	17	—	3.4	2.5	60
G332.302−0.079	16:15:45.8	−50:56:03	40	5.9	60	15	14	8.4	66
G332.307+2.284	16:05:44.0	−49:10:47	1.1	0.026	1.2	0.072	11	8.5	63
G332.644−0.607	16:19:37.1	−51:03:23	36	2.6	120	38	21	13	82
G332.826−0.549	16:20:11.0	−50:53:14	4200	180	4700	290	12	8.1	75
G332.962+0.774	16:15:00.6	−49:50:38	19	1.5	95	43	28	15	−26
G332.987−0.487	16:20:37.7	−50:43:49	8	1.3	10	2.3	12	8.6	80
G333.029−0.063	16:18:56.8	−50:23:54	31	1.3	34	2	11	8.1	78
G333.109−0.502	16:21:14.5	−50:39:16	24	3.3	71	25	21	12	−77
G333.130−0.426	16:21:00.1	−50:35:09	1600	66	2400	160	13	8.7	88
G333.135−0.432	16:21:02.9	−50:35:12	3000	75	3100	120	10	7.7	72
G333.163−0.100	16:19:42.4	−50:19:53	110	0.34	120	8.3	11	8.9	77

Table 7.2 – continued from previous page

Radio name	RA (J2000) (h:m:s)	Dec. (J2000) (d:m:s)	f_{peak} (mJy beam ⁻¹)	Δf_{peak} (mJy beam ⁻¹)	f_{int} (mJy)	Δf_{int} (mJy)	Major (arcsec)	Minor (arcsec)	PA (°)
G336.983−0.183	16:36:12.4	−47:37:58	56	1.9	56	2.7	11	7.7	81
G336.990−0.025	16:35:32.3	−47:31:15	100	5.4	160	12	13	9.7	70
G338.280+0.542	16:38:09.0	−46:11:03	3.8	0.24	4.4	0.4	7	2.3	4.2
G338.566+0.110	16:41:07.1	−46:15:30	8.8	0.32	12	0.64	7.3	2.5	5.7
G338.922+0.624	16:40:15.4	−45:39:03	190	7.9	200	14	12	7.1	−85
G338.925+0.556	16:40:33.5	−45:41:38	12	1.1	15	2.1	7.7	2.3	5.4
G339.282+0.136	16:43:43.1	−45:42:09	3.4	0.11	3.5	0.18	12	6.8	−87
G339.622−0.121	16:46:06.0	−45:36:43	4.9	0.25	5.6	0.41	7.1	2.2	5.3
G339.681−1.207	16:51:06.2	−46:15:59	2	0.25	4.3	0.79	10	2.9	8.3
G339.884−1.259	16:52:04.6	−46:08:33	13	0.92	16	1.7	7.2	2.4	7.3
G339.980−0.539	16:49:14.7	−45:36:32	52	30	180	98	12	6.9	−86
G340.056−0.244	16:48:14.2	−45:21:39	210	9	450	28	8	3.9	8.2

7.1.1 INDIVIDUAL SOURCE DESCRIPTIONS OF CANDIDATE HC HII REGIONS

This appendix provides brief descriptions of each of the candidate HC HII regions identified in this Chapter 3, summarising their key observational properties and associations.

7.1.1(a) PROTOSTELLAR

G326.475+0.703 (Figure 7.1a): The detected radio emission is closely associated with the MMB source G326.475+00.703 (Green et al. 2012, which is offset by 0.8 arcsec. There is a second MMB source located 29.1 arcsec to the south east (G326.476+00.695; Green et al. 2012) that is associated with bright mid-infrared emission and has been previously classified as a YSO by the Red MSX Source (RMS) survey (G326.4755+00.6947; Lumsden et al. 2013). The MMB source associated with the radio emission is mid-infrared dark with a counterpart only appearing at wavelengths of $70\mu\text{m}$ and longer. The source itself is coincident with the peak of the strong compact dust emission and so consistent with being a deeply embedded protostellar object. The radio emission is therefore associated with the youngest embedded object, consistent with this radio source being a very young compact HII region. There is no 5 GHz radio counterpart, however it has been covered by the CORNISH-South survey (Irabor et al., 2023) and we can use the mean survey sensitivity of 0.33 mJy (3σ) to determine a lower limit for the spectral index of +1.14. This source appears to be a very young and embedded object that is associated with an optically thick ionized nebula making it a strong HC HII region candidate.

G338.566+0.110 (Figure 7.1b): The radio source is tightly correlated with the position of the MMB source G338.566+00.110 (Caswell et al. 2011) with an offset of 2.2 arcsec, and coincident with a $70\mu\text{m}$ point source, which is itself located towards the peak of the dust emission. There is a 5 GHz counterpart for this radio source detected by the CORNISH-South (G338.5660+0.1096, offset = 0.7 arcsec; Irabor et al. 2023)

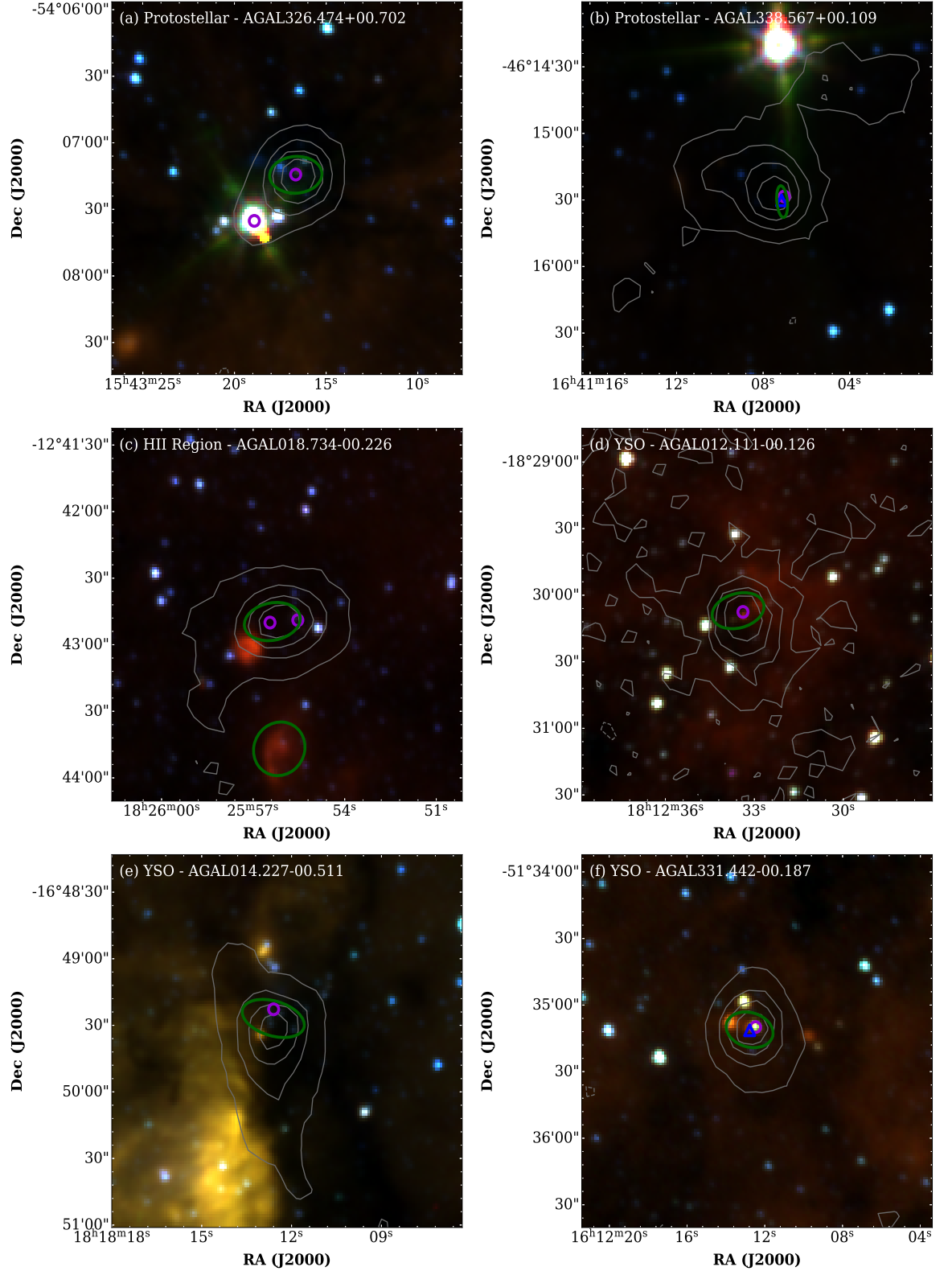


FIGURE 7.1: Three colour images using IRAC wavebands at 4.5, 5.8 and 8.0 μm for our HCHII region candidates. The green ellipse shows the position of the high-frequency (23.7 GHz) radio source and the purple circles shows the position of the methanol maser. The blue triangles show the position of the low-frequency (5 GHz) radio counterpart and the grey contours trace 870 μm dust emission from ATLASGAL. The ATLASGAL classification is given in the top left.

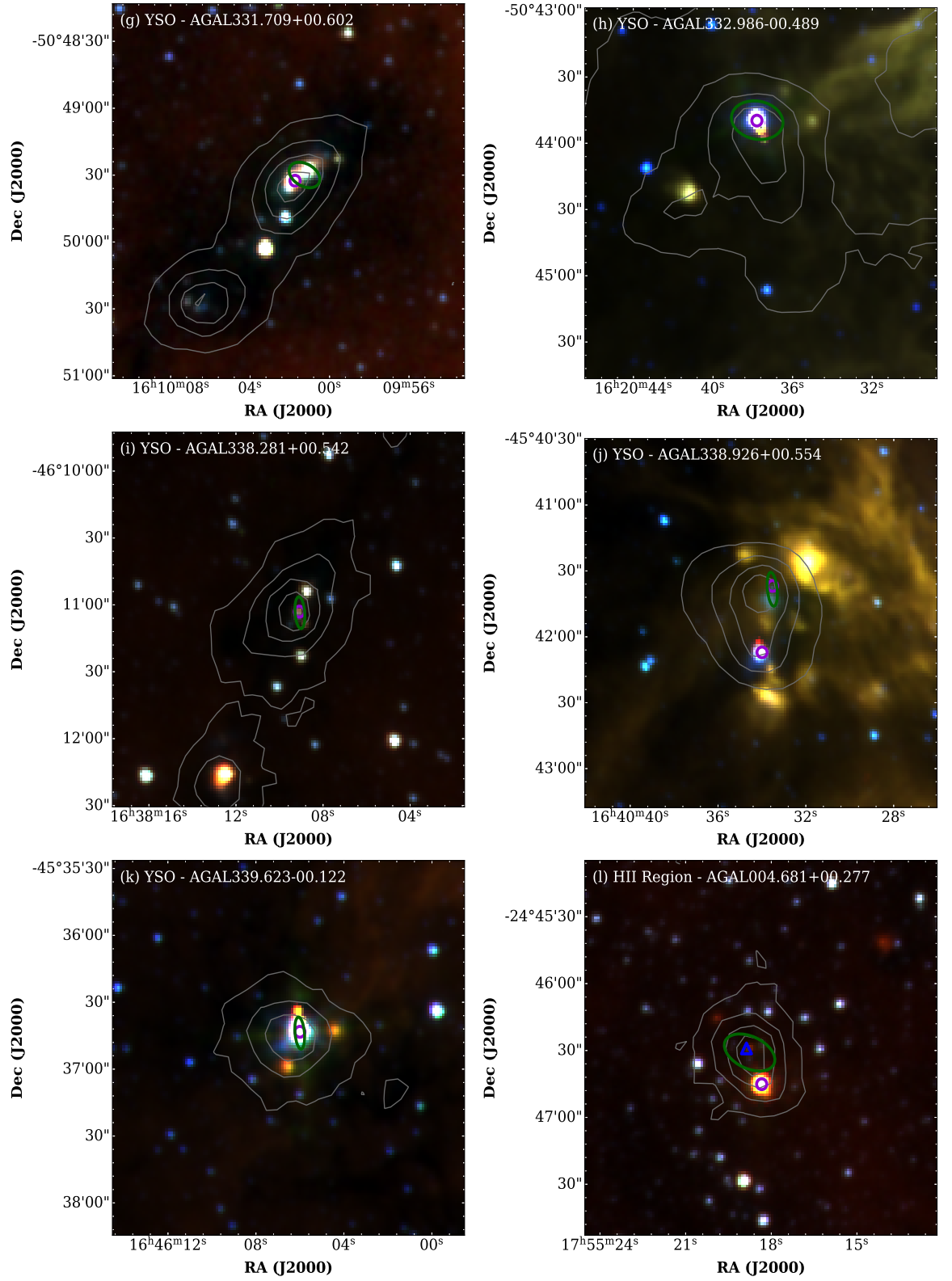


FIGURE 7.1: Cont.

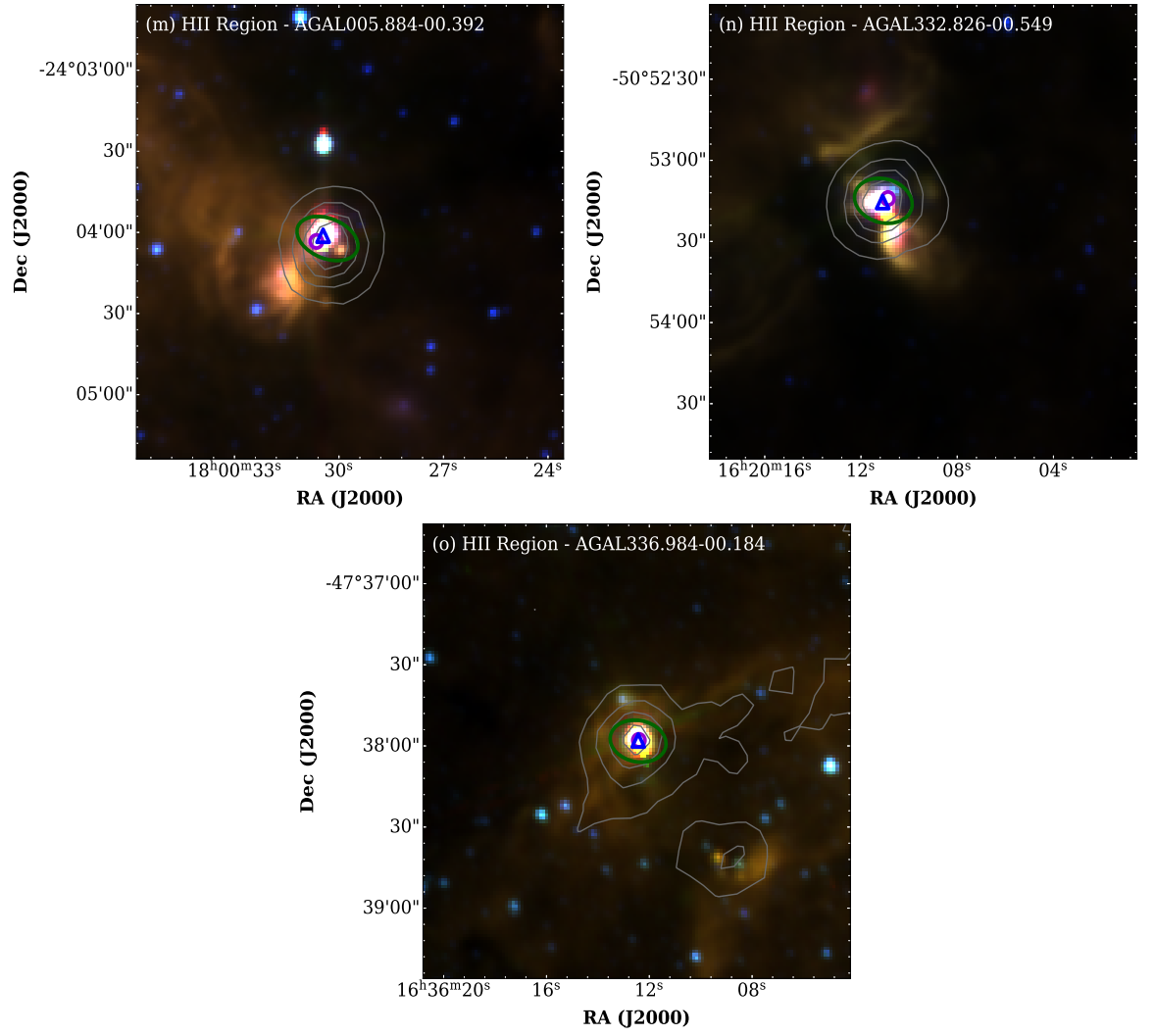


FIGURE 7.1: Cont.

and, using the integrated flux density (4.98 ± 0.19 mJy) we determine the spectral index to be 0.37 ± 0.03 . The coincidence of the methanol-maser emission, far-infrared point source, dust emission and high- and low-frequency radio counterparts all point to this being a strong HC HII region candidate.

G339.681–1.207: This source has compact high-frequency radio emission that is coincident with two methanol masers G339.681–01.208 and G339.682–01.207 (Caswell et al. 2011) that are offset by 2.4 arcsec and 2.6 arcsec respectively. Both masers are coincident with the peak of the dust emission. This source is located outside the GLIMPSE region and so there are no IRAC data available but there is compact emission at $24\mu\text{m}$ (Carey et al., 2009) and $70\mu\text{m}$ (Molinari et al., 2010a), which is coincident with the position of the maser and the peak in the dust continuum. This region was observed at 4.8 and 8.6 GHz as part of the RMS survey but no radio emission was detected above 3σ at either frequency, i.e. 0.3 mJy and 0.6 mJy respectively (RMS source G339.6816–01.2058; Urquhart et al. 2007) leading the RMS team to classify this source as a YSO. Using the 4.8 GHz radio continuum upper limit we determine a lower limit for the spectral index of +1.16, confirming this object is an excellent HC HII region candidate.

G018.735–0.227 (Figure 7.1c): This radio source is one of two within the field in which the radio detection is coincident with the MMB methanol maser G018.735–00.227 (Green et al. 2010) and water maser 18.735–0.227 (Titmarsh et al., 2016). The offset between the radio, methanol, and water maser positions is 1.5 and 1.8 arcsec, respectively and both are coincident with the centre of the compact dust clump. This clump has been classified as an HII region by the ATLASGAL team (Urquhart et al., 2022), however, inspection of the $8\mu\text{m}$ mid-infrared environment reveals that the extended emission associated with the embedded HII region is offset from the high-frequency radio emission, which is located to the south east of the dust clump. No compact IRAC emission is found within the high-frequency radio ellipse, but searching the MIPS GAL $24\mu\text{m}$ catalogue (Gutermuth & Heyer, 2015) reveals a discrete point

source coincident with the radio emission. Considering that the radio emission is closely associated with both methanol and water maser emission the clump is likely to be associated with outflows and active accretion.

This source was observed at 5 GHz by Hu et al. (2016) who reported the detection of a marginally resolved point source with a peak and integrated flux density of $1.02 \text{ mJy beam}^{-1}$ and 1.22 mJy , respectively. This 5 GHz source is located 1.34 arcsec from the maser position and is coincident with the high-frequency radio source. Using the integrated 5 GHz flux density we find the spectral index for this radio source to be 0.20 ± 0.12 , indicating this HII region is more likely to be optically thin; however, the lack of a $8\mu\text{m}$ source makes this an interesting region and difficult to explain. One possible explanation could be that we are observing a HII region located on the far side of a dense molecular gas cloud. More information is needed to make a reliable determination of the nature of this radio emission.

7.1.1(b) YSO

G012.112–0.127 (Figure 7.1d): This source is close to the MMB methanol maser G012.112–00.126 (Green et al. 2010) with an offset of only 2.5 arcsec . Strong dust emission from compact clump is coincident with the radio and maser emission. The IRAC images reveal an unresolved mid-infrared point source towards the centre of the clump. This source is not associated with a 5 GHz radio counterpart but we can calculate a lower limit for the spectral index to be -0.87 from an upper limit (0.42 mJy) obtained from the CORNISH data, which is inconclusive. Despite the poor constraint on the spectral index, this source appears to be young, compact and embedded, making it a good HC HII region candidate.

G014.229–0.510 (Figure 7.1e): The detected high-frequency radio emission is close to (offset $\sim 4 \text{ arcsec}$) with the MMB methanol maser G014.230–00.509 (Green et al. 2010) and the peak of the dust emission. The mid-infrared environment is dark at $8\mu\text{m}$ and $22\mu\text{m}$ but there is a distinct point source at $70\mu\text{m}$ and so this is more likely to be protostellar in origin rather than a YSO as classified by the ATLASGAL team.

There is no 5 GHz radio counterpart associated with the high-frequency radio emission, however, the position has been covered by the CORNISH survey and so we are able to determine a lower limit using a upper limit value of 0.37 mJy for the 5 GHz emission. We measure the lower limit to the spectral index to be -0.26 , which is inconclusive. The overlap of the star-forming tracers and lack of a mid-infrared counterpart indicate this is a good HC HII region candidate.

G331.442–0.187 (Figure 7.1f): This radio source is close to a mid-infrared point source and MMB methanol maser (offset by 3 arcsec from G331.442–00.187; Caswell et al. 2011). It is positioned near the peak of the dust emission and is associated with $22\mu\text{m}$ WISE (Wright et al., 2010) and $70\mu\text{m}$ Hi–GaL (Molinari et al., 2010a) emission, confirming that this is an embedded and compact HII region. A 5 GHz counterpart of this radio source is detected in the CORNISH-South data (G331.4420–0.1874, offset = 0.3 arcsec; Irabor et al. 2023). Using the integrated flux density, we determine the spectral index to be 0.08 ± 0.06 , which indicates the nebula is optically thin and that this is more likely to be an UC HII region.

G331.710+0.604 (Figure 7.1g): This source is offset (5.3 arcsec) from the MMB methanol maser G331.710+00.603 (Caswell et al. 2011) and coincident with the peak of the dust emission and a $8\mu\text{m}$ mid-infrared point source. It has no 5 GHz radio counterpart, however it has been covered by the CORNISH-South survey (Irabor et al. 2023) and we can use the mean survey sensitivity of 0.33 mJy (3σ) to determine a lower limit for the spectral index of $+0.64$. The coincidence of dust and embedded mid-infrared sources is consistent with this being a deeply embedded young star also being associated with high-frequency radio emission makes this source a good HC HII region candidate.

G332.987–0.487 (Figure 7.1h): The high-frequency radio emission is tightly correlated with a methanol maser G332.987–00.487 (offset = 1.8 arcsec; Caswell et al. 2011) and a mid-infrared point source, but is slightly offset from the peak of the dust

emission. Large-scale extended emission is found to the north and west of the radio and MMB positions. There is no 5 GHz counterpart for this source, however, we can calculate a lower limit of $+1.74$ from the CORNISH-South survey sensitivity ($3\sigma = 0.33$ mJy; Irabor et al. 2023), consistent with the radio emission being associated with an optically thick HII region. This is therefore an excellent HC HII region candidate.

G338.280+0.542 (Figure 7.1i): This high-frequency radio source is tightly associated with MMB maser G338.280+00.542 (offset < 1 arcsec; Caswell et al. 2011) and coincident with the peak of the dust emission. The radio emission is mid-infrared dark at $8\mu\text{m}$ however, at $22\mu\text{m}$ we see two distinct point sources. There is no 5 GHz radio counterpart, however, there are upper limits available at 4.8 and 8.6 GHz from the RMS survey (i.e. 3σ upper limits are 0.4 mJy and 1.2 mJy respectively; Urquhart et al. 2007) from which we can determine a value of $+1.57$ as a lower limit to the spectral index. The coincidence of this radio source with the star-formation tracers and the lower limit for the spectral index make this a strong HC HII region candidate.

G338.925+0.556 (Figure 7.1j): The mid-infrared image reveals a larger extended structure to the west. The radio source is coincident with a dense dust clump located on the edge of the extended mid-infrared source and the methanol maser G338.925+00.557; (Caswell et al. 2011), which is offset by 1.0 arcsec. Inspection of the mid-infrared image reveals a small group of point sources located towards the centre of the clump, indicating the presence of a small protocluster. There is no 5 GHz counterpart but, again using archival data from the RMS survey, we estimate the 3σ upper limits of 0.5 mJy and 0.5 mJy at 4.8 and 8.6 GHz, respectively (RMS source G338.9237+00.5618; Urquhart et al. 2007), and use these to determine a lower limit of $+2.29$ for the spectral index. This source is therefore an excellent HC HII region candidate.

G339.622−0.121 (Figure 7.1k): The high-frequency radio emission is coincident with a mid-infrared bright point source, which itself is located towards the centre

of the dust clump and is associated with the MMB methanol maser G339.622–00.121 (Caswell et al. 2011) that is offset by 0.7 arcsec. There is no 5 GHz counterpart for this source. However, again using the CORNISH-South survey sensitivity ($3\sigma=0.33$ mJy; Irabor et al. 2023), we calculate a lower limit for the spectral index of +1.42. The spectral index and coincidence of the radio emission, methanol maser, dense gas and mid-infrared point sources all make this an excellent HC HII region candidate.

7.1.1(c) OPTICALLY THICK HII REGIONS

Below we discuss four sources identified in this work and by the ATLASGAL team as being HII regions that have a positive spectral index, making them potential HC HII region candidates.

G004.680+0.277 (Figure 7.1l): The radio source is located towards the centre of ATLASGAL clump AGAL004.681+00.277 (Contreras et al., 2013) but is offset by 15.3 arcsec to the north from the central maser position. This is tightly correlated with a bright mid-infrared point source. Additionally, there is a weak mid-infrared point source located towards the centre of the dust clump, that is coincident with the position of the high frequency radio ellipse. We have looked at the corresponding $24\mu\text{m}$ MIPS GAL data (Carey et al., 2009; Gutermuth & Heyer, 2015), which also reveals the presence of a discrete point source towards the centre of the dust clump and is coincident with the IRAC and radio sources. The centre of the clump is also host to a 5 GHz radio counterpart allowing us to determine a spectral index of $+0.39 \pm 0.07$, which is marginally optically thick. Despite this source being below the estimated optical depth threshold the correspondence of compact dust emission, the weak mid-infrared emission and positive spectral index suggests it is in an early stage of its evolution and for these reasons we consider this source to be a HC HII region candidate.

G005.885–0.392 (Figure 7.1m): This 23.7 GHz radio detection is part of a more extended, filamentary type structure and is a well known UC HII region (Bronf-

man et al., 1996). The radio emission overlaps with MMB methanol maser G005.885–00.393 (offset by 4.5 arcsec; Caswell 2010) and water maser 5.885–0.393 (offset by 2.4 arcsec; Titmarsh et al. 2016). The high-frequency radio source has a 5 GHz radio counterpart (5.885–0.392; Becker et al. 1994) that is offset by 1.9 arcsec and is coincident with the peak of the dust emission. We calculate the spectral index to be $+0.81 \pm 0.02$ indicating the emission is optically thick at 23.7 GHz. Inspection of the mid-infrared environment for this dust clump reveals that the high-frequency radio detection is embedded within a complicated and somewhat extended HII region. Despite this, with the data we have available, the 23.7 GHz radio emission is still unresolved and positionally correlated to all the star forming tracers discussed and is therefore a highly interesting source for further investigation.

G332.826–0.549 (Figure 7.1n): The high-frequency radio emission is coincident with the peak of the strong compact dust emission and is correlated with a MMB methanol maser G332.826–00.549 (Caswell et al., 2011); offset 2.2 arcsec. The centre of the clump is also host to a 5 GHz radio counterpart G332.8260–00.5493 (Urquhart et al. 2007 offset; 0.5 arcsec) allowing us to determine a spectral index of $+0.77 \pm 0.07$. The mid-infrared image reveals a complicated structure but the radio source and maser are coincident with a bright $8\mu\text{m}$ point source. Based on the associations explored we consider this a strong HC HII region candidate.

G336.983–0.183 (Figure 7.1o): The high frequency radio emission is located towards the centre of the dust clump and is associated with MMB methanol maser G336.983–00.183 (Caswell et al., 2011) and a 5 GHz radio source G336.9833–00.1832 (Urquhart et al. 2007) both offset by 1.1 arcsec. Inspection of the mid-infrared image reveals that the radio emission is coincident with a mid-infrared point source at $8\mu\text{m}$. We measure the spectral index of the emission to be $+0.72 \pm 0.03$, confirming the ionized nebula is optically thick. From the close correlation of star formation tracers and spectral index measurement, we can say this source is a strong HC HII region candidate.

7.2 CHAPTER 4

7.3 CHAPTER 5

In Fig. 7.2 we present the SEDs for all the HII regions identified in this work.

Table 7.3 – Observational parameters from all observed fields. The field names and pointing centres of the observations are based on the radio names and positions.

Field name	RA (J2000) (h:m:s)	Dec. (J2000) (d:m:s)	Field rms		Beam size 18 GHz		Beam size 24 GHz	
			(mJy)	(mJy)	(arcsec)	($^{\circ}$)	(arcsec)	($^{\circ}$)
G002.143+0.009	17:50:36.02	-27:05:46.9	0.1	0.1	1.8	0.5	1.7	-12.4
G002.614+0.134	17:51:12.27	-26:37:38.8	0.2	0.2	1.9	0.5	1.8	-11.6
G003.438-0.349	17:54:55.66	-26:09:47.4	0.1	0.2	2	0.5	1.9	-12.9
G003.910+0.001	17:54:38.75	-25:34:44.7	0.5	0.4	2.1	0.5	2	-12.1
G004.680+0.277	17:55:18.83	-24:46:29.5	0.1	0.1	2.2	0.5	2.1	-11.3
G005.885-0.392	18:00:30.39	-24:04:00.1	15.9	16.6	2.2	0.5	2.1	-11.2
G011.904-0.141	18:12:11.43	-18:41:29.4	0.3	0.3	3.8	0.4	3.2	-7.9
G011.937-0.616	18:14:01.05	-18:53:24.9	1.1	1.9	3.8	0.4	3.1	-7.9
G012.112-0.127	18:12:33.6	-18:30:06.8	0.1	0.1	4	0.4	3.3	-7.5
G012.199-0.034	18:12:23.61	-18:22:54.7	0.2	0.2	4.2	0.4	3.5	-7.2
G012.208-0.102	18:12:39.68	-18:24:20.9	0.5	0.5	4.2	0.4	3.5	-7
G014.104+0.092	18:15:45.1	-16:38:51.3	0.1	0.1	8.6	0.3	10.2	-6.5
G014.229-0.510	18:18:12.72	-16:49:26.7	0.1	0.1	5.1	0.4	9.8	-7.3
G014.599+0.020	18:17:01.2	-16:14:39.1	0.1	0.1	7.7	0.4	10.2	-6
G018.461-0.004	18:24:36.33	-12:51:04.2	2	1.4	7.6	0.4	10.8	-5.4
G018.665+0.029	18:24:52.59	-12:39:19.3	0.1	0.1	8	0.4	10.7	-5.2
G018.735-0.227	18:25:56.46	-12:42:48.8	0.1	0.1	7.7	0.4	10.6	-5.2
G326.475+0.703	15:43:16.63	-54:07:15.0	0.1	0	0.9	0.5	0.7	-36.6
G327.402+0.445	15:49:19.32	-53:45:14.4	0.3	0.4	0.9	0.5	0.7	-37.9
G331.130-0.243	16:10:59.41	-51:50:23.5	0.3	0.2	0.9	0.5	0.7	-34.2
G331.442-0.187	16:12:12.77	-51:35:11.0	0.2	0.1	0.9	0.5	0.7	-34.6
G331.542-0.067	16:12:09.02	-51:25:47.5	1.5	1	0.9	0.5	0.7	-35.3
G331.557-0.120	16:12:27.28	-51:27:32.4	0.2	0.2	0.9	0.5	0.7	-35.1
G331.710+0.604	16:10:01.44	-50:49:28.9	0	0	0.9	0.5	0.7	-40.2
G332.826-0.549	16:20:11.05	-50:53:14.2	6.8	7	0.9	0.5	0.7	-39.7
G332.987-0.487	16:20:37.78	-50:43:49.7	0.1	0.1	0.9	0.5	0.7	-40.1
G333.029-0.063	16:18:56.86	-50:23:54.2	0.1	0.2	0.9	0.5	0.7	-39.6
G333.133-0.429	16:21:01.68	-50:35:09.9	7.9	5.5	0.9	0.5	0.7	-40.6
G333.163-0.100	16:19:42.37	-50:19:53.6	0.1	0.1	0.9	0.5	0.7	-39.2
G336.983-0.183	16:36:12.41	-47:37:58.3	0.3	0.2	0.9	0.5	0.8	-30

Table 7.3 – continued from previous page

Field name	RA (J2000) (h:m:s)	Dec. (J2000) (d:m:s)	Field rms		Beam size 18 GHz		Beam size 24 GHz	
			(mJy)	(mJy)	(arcsec)	($^{\circ}$)	(arcsec)	($^{\circ}$)
G338.280+0.542	16:38:09.12	-46:11:04.2	0	0	1	0.5	0.9	-23.1
G338.566+0.110	16:41:07.15	-46:15:30.5	0.1	0.1	1	0.5	0.9	-23.7
G338.925+0.556	16:40:33.54	-45:41:37.6	0.1	0.1	1	0.5	0.9	-23.5
G339.282+0.136	16:43:43.08	-45:42:08.6	0.1	0.1	1	0.5	0.9	-23.5
G339.622-0.121	16:46:06.01	-45:36:43.8	0.1	0	1	0.5	0.9	-23.3
G339.681-1.207	16:51:06.21	-46:15:58.0	0.1	0.1	1	0.5	0.8	-24.3
G339.884-1.259	16:52:04.65	-46:08:33.9	0.1	0.1	1	0.5	0.8	-24.1
G339.980-0.539	16:49:14.72	-45:36:32.4	0.2	0.3	1	0.5	0.8	-24.3
G340.056-0.244	16:48:14.22	-45:21:39.1	0.5	0.6	1	0.5	0.8	-23.7
								-17.1
								-17.3
								-16.6
								-17.2
								-17.4
								-18
								-17.7
								-17.2
								-17.5

Table 7.4 - Observational field parameters from all observed fields. The field names and pointing centers are based on the MMB names and positions. Fields marked with a 'z' in the "Detection" column were not observed as part of the high-resolution follow-up but were included in the low-resolution observations.

Field name	RA		Dec. (J2000) (d:m:s)	Low Resolution				High Resolution				
	(J2000) (h:m:s)	(J2000) (d:m:s)		rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)	Position angle ($^{\circ}$)	rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)
G300.504-00.176	12:30:03.57	-62:56:48.8	3.1	Y	10	8.8	-86	2.4	-	7.5	6.7	79
G300.969+01.148	12:34:53.28	-61:39:39.9	40	Y	10	8.8	89	33	Y	7.5	6.8	74
G301.136-00.226	12:35:35.13	-63:02:32.6	59	Y	10	8.8	-85	58	Y	7.5	6.8	78
G302.032-00.061	12:43:31.92	-62:55:06.6	56	Y	10	8.9	88	41	Y	7.6	6.9	78
G302.034+00.625	12:43:43.44	-62:13:58.4	0.11	Y	9.9	9.1	-78	0.14	N	7.6	6.7	86
G302.455-00.741	12:47:08.64	-63:36:30.2	0.29	N	9.9	9.3	-76	0.19	N	7.6	6.8	85
G304.367-00.336	13:04:09.81	-63:10:20.2	0.13	N	10	9.1	-89	0.15	N	7.4	6.9	-80
G304.887+00.635	13:08:11.95	-62:10:21.7	0.12	N	9.9	9.1	-82	0.17	N	7.5	6.7	-75
G305.199+00.005	13:11:17.20	-62:46:45.8	51	N	9.3	8.7	-64	13	N	7	6.5	-57
G305.200+00.019	13:11:16.92	-62:45:55.0	100	N	9.3	8.6	-59	60	N	7	6.5	-47
G305.208+00.206	13:11:13.70	-62:34:41.5	21	Y	9.1	8.6	-62	9.2	-	6.9	6.6	-35
G305.248+00.245	13:11:32.47	-62:32:09.2	14	N	9.2	8.6	-84	5.3	N	6.8	6.5	-33
G305.362+00.150	13:12:35.85	-62:37:17.7	15	Y	9.1	8.6	-73	7.7	-	6.9	6.5	-31
G305.366+00.184	13:12:36.74	-62:35:14.6	79	N	9.1	8.6	-64	45	N	6.9	6.6	-21
G305.475-00.096	13:13:45.74	-62:51:28.4	0.47	N	9.1	8.7	-42	0.6	N	7.1	6.6	-5.9
G305.563+00.013	13:14:26.90	-62:44:29.4	9.1	Y	9.2	8.7	-20	4.9	-	7.2	6.4	-8.8
G305.573-00.342	13:14:49.12	-63:05:38.4	0.32	N	9.9	8.3	-7.9	0.48	N	7.2	6.3	-8
G305.615-00.344	13:15:11.30	-63:05:29.7	0.23	N	9.7	9	22	0.29	N	7.4	6.4	24
G305.799-00.245	13:16:43.22	-62:58:32.8	1.8	Y	9.6	9	26	1.3	Y	7.4	6.4	23
G305.822-00.115	13:16:48.72	-62:50:38.0	0.19	N	9.7	8.9	30	0.22	N	7.3	6.4	25
G305.887+00.017	13:17:15.52	-62:42:23.0	0.29	Y	9.8	8.8	28	0.23	N	7.2	6.4	36
G305.940-00.164	13:17:53.04	-62:52:50.5	0.15	N	9.9	8.8	29	0.23	N	7.1	6.4	42
G306.322-00.334	13:21:23.01	-63:00:29.5	3.2	N	10	8.7	25	1.3	N	7.3	6.3	29
G308.056-00.396	13:36:32.16	-62:49:05.5	12	Y	9.5	9.1	38	9.9	Y	7	6.6	30
G308.075-00.411	13:36:43.51	-62:49:45.1	8.6	N	9.5	9	18	3.8	N	7.3	6.5	32
G308.651-00.507	13:41:50.18	-62:49:05.1	0.22	Y	12	9.1	-65	0.52	Y	9.1	6.8	-67
G308.686+00.530	13:40:25.32	-61:47:37.6	0.7	N	12	9.1	-67	0.41	N	9.2	6.7	-70
G308.754+00.549	13:40:57.6	-61:45:43.5	3.3	N	12	9	-66	1.1	N	9.1	6.7	-67

Table 7.4 – continued from previous page

Field name	RA		Dec. (J2000) (d:m:s)	Low Resolution			High Resolution					
	(J2000) (h:m:s)	(J2000) (d:m:s)		rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)	Position angle (°)	rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)
G308.918+00.123	13:43:01.84	-62:08:52.0	23	Y	12	9	-67	16	-	9.1	6.8	-65
G309.384-00.135	13:47:23.97	-62:18:11.8	0.28	Y	12	9.1	-65	0.33	Y	9.2	6.7	-68
G309.901+00.231	13:51:01.05	-61:49:55.9	0.18	N	12	9.1	-69	0.28	N	9.2	6.8	-68
G309.921+00.479	13:50:41.78	-61:35:10.3	74	Y	12	9	-67	74	Y	9.2	6.7	-69
G310.144+00.760	13:51:58.44	-61:15:41.4	0.58	Y	10	8.8	87	0.47	Y	7.6	6.7	82
G310.180-00.122	13:54:01.77	-62:06:34.5	0.59	N	10	8.9	86	0.38	N	7.6	6.9	78
G311.230-00.032	14:02:27.48	-61:45:14.4	0.18	N	10	8.7	-86	0.28	N	7.7	6.8	-87
G311.628+00.266	14:04:59.20	-61:21:29.5	53	N	10	8.7	-86	25	N	7.7	6.8	-85
G311.643-00.380	14:06:38.76	-61:58:23.1	19	Y	10	8.6	-85	16	Y	7.7	6.9	-83
G311.947+00.142	14:07:49.72	-61:23:08.1	0.3	N	10	8.7	-87	0.43	N	7.7	6.7	-83
G312.071+00.082	14:08:58.2	-61:24:23.7	0.95	N	10	8.7	-87	0.5	N	7.6	6.8	-83
G312.108+00.262	14:08:49.32	-61:13:24.9	1.6	N	10	8.8	89	0.49	N	7.6	6.7	84
G312.307+00.661	14:09:24.96	-60:47:00.6	2.4	Y	10	9	88	1.9	Y	7.7	6.6	78
G312.598+00.045	14:13:15.02	-61:16:53.7	5.3	Y	10	8.5	-36	3.7	-	7.3	6.4	-37
G313.469+00.190	14:19:40.94	-60:51:47.1	19	N	10	8.5	-31	10	N	7.5	6.4	-26
G313.577+00.325	14:20:08.56	-60:42:00.7	0.26	N	11	8.5	-26	0.47	N	7.6	6.4	-26
G313.705-00.190	14:22:34.72	-61:08:26.8	0.22	N	11	8.5	-24	0.41	N	7.6	6.4	-26
G313.767-00.863	14:25:01.72	-61:44:58.2	0.26	N	11	8.5	-27	0.46	N	7.7	6.4	-26
G313.994-00.084	14:24:30.79	-60:56:28.3	0.26	N	-	-	-	0.55	N	-	-	-
G314.221+00.273	14:25:12.88	-60:31:38.2	2.5	Y	11	8.2	-27	1.5	Y	7.8	6.3	-27
G314.320+00.112	14:26:26.20	-60:38:31.2	0.19	N	11	8.3	-27	0.43	N	8	6.3	-27
G315.803-00.575	14:39:46.46	-60:42:39.6	0.1	N	9.2	9.1	-19	0.37	N	6.9	6.8	86
G316.359-00.362	14:43:11.20	-60:17:13.2	2.8	Y	9.2	9.1	-39	2.2	-	7	6.7	83
G316.381-00.379	14:43:24.21	-60:17:37.3	1.2	N	9.2	9	-25	0.78	N	6.9	6.7	77
G316.412-00.308	14:43:23.32	-60:13:00.8	0.32	N	9.2	9	-21	0.23	N	7	6.7	62
G316.640-00.087	14:44:18.45	-59:55:11.6	0.44	N	9.1	9.1	-11	0.25	N	7	6.6	69
G316.811-00.057	14:45:26.42	-59:49:16.3	92	N	9.2	9	13	0.25	N	-	-	-
G317.029+00.361	14:45:35.54	-59:20:58.5	0.59	N	9.3	8.9	22	0.35	N	6.8	6.7	49

Table 7.4 – continued from previous page

Field name	RA		Dec. (J2000) (d:m:s)	Low Resolution			High Resolution					
	(J2000) (h:m:s)	(J2000) (d:m:s)		rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)	Position angle (°)	rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)
G317.061+00.256	14:46:10.32	-59:25:50.5	0.88	N	9.3	9	38	0.45	N	6.8	6.7	20
G317.466-00.402	14:51:19.68	-59:50:50.6	0.2	N	13	9	-75	0.29	N	9.4	6.6	-83
G317.701+00.110	14:51:11.68	-59:17:02.0	0.15	N	13	9.1	-73	0.23	N	9.3	6.7	-82
G318.044-01.404	14:59:08.61	-60:28:25.3	0.12	N	13	9	-78	0.22	N	9.4	6.6	-82
G318.050+00.087	14:53:42.67	-59:08:52.4	0.67	Y	13	9.1	-71	0.72	Y	9.3	6.6	-80
G318.472-00.214	14:57:42.86	-59:13:15.9	0.16	N	13	9	-74	0.25	N	9.3	6.7	-81
G318.948-00.196	15:00:55.39	-58:58:51.9	5	N	13	9	-75	0.96	N	9.4	6.6	-82
G319.163-00.421	15:03:13.72	-59:04:30.3	38	Y	13	9	-75	27	-	9.4	6.7	-83
G319.836-00.197	15:06:54.64	-58:33:00	0.21	N	13	9.1	-73	0.25	N	9.3	6.7	-82
G320.123-00.504	15:10:00.16	-58:40:18.1	1.3	N	10	8.6	71	1.9	N	7.3	6.6	79
G320.231-00.284	15:09:51.93	-58:25:38.6	24	Y	10	8.7	72	16	Y	7.2	6.5	74
G320.244-00.562	15:11:01.60	-58:39:37.8	0.16	N	11	8.3	78	0.18	N	7.7	6.4	72
G320.285-00.308	15:10:19.00	-58:25:16.6	2.3	N	10	8.7	73	0.97	N	7.2	6.5	73
G320.414+00.109	15:09:33.33	-57:59:46.6	4.9	Y	9.8	8.6	74	3.1	-	7.2	6.4	76
G320.780+00.248	15:11:23.47	-57:41:25.0	2.5	Y	9.7	8.6	72	1.2	-	7.2	6.4	80
G321.030-00.485	15:15:51.79	-58:11:17.8	9.4	Y	9.8	8.8	76	4.4	-	7.2	6.4	77
G321.148-00.529	15:16:48.38	-58:09:50.0	4.1	N	9.5	8.6	61	1.9	N	7.2	6.3	63
G321.704+01.168	15:13:44.71	-56:25:34.3	35	Y	9.6	8.8	69	17	-	7.2	6.3	60
G322.158+00.636	15:18:34.63	-56:38:25.4	110	Y	9.5	8.8	60	62	-	7.2	6.4	61
G322.705-00.331	15:25:47.52	-57:09:15.4	5.1	Y	9.6	8.6	61	2.7	-	7.1	6.4	73
G323.459-00.079	15:29:19.32	-56:31:22.8	60	Y	9.7	8.5	59	49	Y	7.1	6.4	76
G323.740-00.263	15:31:45.45	-56:30:50.0	2.2	Y	9.7	8.5	59	0.95	-	7.1	6.3	76
G323.766-01.370	15:36:37.68	-57:24:01.4	0.25	Y	11	8.8	-78	0.36	-	7.7	6.5	-87
G323.793-00.397	15:32:38.08	-56:35:36.6	0.19	N	11	8.4	-80	0.38	N	8	6.3	-87
G323.799+00.017	15:30:57.12	-56:15:01.4	1.3	N	10	8.5	-79	0.64	N	7.9	6.3	-88
G324.716+00.342	15:34:57.48	-55:27:23.7	0.59	N	11	8.5	-79	0.51	N	7.9	6.3	-88
G324.915+00.158	15:36:51.16	-55:29:22.9	0.18	N	10	8.5	-80	0.3	N	7.9	6.3	-90
G324.923-00.568	15:39:57.64	-56:04:08.4	29	Y	11	8.4	-80	20	Y	7.9	6.3	-89

Table 7.4 – continued from previous page

Field name	RA		Dec. (J2000) (d:m:s)	Low Resolution			High Resolution					
	(J2000) (h:m:s)	(J2000) (d:m:s)		rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)	Position angle (°)	rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)
G326.323−00.393	15:47:04.58	−55:04:50.5	0.23	N	11	8.4	−82	0.37	N	7.9	6.3	−84
G326.448−00.748	15:49:18.62	−55:16:51.6	0.58	Y	11	8.4	−81	0.57	Y	7.8	6.3	−85
G326.608+00.799	15:43:36	−53:57:47.1	1.2	N	10	8.7	−76	0.56	N	7.8	6.3	−83
G326.641+00.611	15:44:33.33	−54:05:31.5	52	N	10	8.7	−74	21	N	7.8	6.3	−85
G326.662+00.520	15:45:02.95	−54:09:03.2	7	Y	10	8.6	−76	6.1	−	7.8	6.3	−84
G326.859−00.677	15:51:14.18	−54:58:04.8	0.19	N	10	8.6	−76	0.35	N	7.9	6.3	−85
G327.120+00.511	15:47:32.73	−53:52:38.2	0.65	N	9.6	8.7	−80	0.44	N	7.3	6.4	84
G327.291−00.578	15:53:07.65	−54:37:06.2	110	N	9.9	8.5	86	37	N	7.4	6.5	80
G327.395+00.197	15:50:20.06	−53:57:07.5	0.14	N	9.7	8.7	−86	0.19	N	7.3	6.4	78
G327.566−00.850	15:55:47.61	−54:39:11.5	1.5	N	9.6	8.6	−86	0.8	N	7.4	6.5	86
G327.590−00.094	15:52:36.81	−54:03:18.7	0.13	N	9.7	8.6	89	0.17	N	7.3	6.4	74
G327.618−00.111	15:52:50.20	−54:03:00.7	0.2	N	9.7	8.6	89	0.2	N	7.4	6.4	72
G327.710−00.394	15:54:32.97	−54:12:36.3	4.9	N	9.6	8.6	84	1.7	N	7.4	6.4	72
G327.808−00.634	15:56:06.91	−54:19:54.4	0.33	N	9.6	8.5	82	0.22	N	7.3	6.5	68
G327.945−00.115	15:54:33.91	−53:50:44.1	0.63	N	9.5	8.8	73	0.4	N	7.2	6.5	82
G328.140−00.432	15:56:57.74	−53:57:48.6	0.12	N	9.5	8.7	75	0.17	N	7.2	6.5	82
G328.164+00.587	15:52:42.36	−53:09:50.4	0.39	Y	9.5	8.7	73	0.31	Y	7.1	6.4	73
G328.237−00.547	15:57:58.27	−53:59:22.5	2.3	Y	9.4	8.5	78	1.8	Y	7.2	6.4	77
G328.254−00.532	15:57:59.76	−53:58:00.4	1.6	N	9.5	8.6	80	1	N	7.1	6.4	75
G328.809+00.633	15:55:48.69	−52:43:05.5	130	Y	13	8.8	84	96	Y	9.6	6.5	88
G328.942+00.565	15:56:46.17	−52:41:04.9	6	Y	13	8.9	84	3.2	−	9.5	6.5	89
G329.031−00.198	16:00:30.31	−53:12:27.3	0.23	N	13	8.7	82	0.39	N	9.6	6.6	89
G329.066−00.308	16:01:09.93	−53:16:02.6	0.14	N	13	8.8	84	0.33	N	9.5	6.6	−89
G329.183−00.314	16:01:47.01	−53:11:43.4	0.42	Y	13	8.9	85	0.47	Y	9.5	6.4	−86
G329.272+00.115	16:00:21.76	−52:48:48.2	4.1	Y	13	8.8	84	1.6	Y	9.3	6.7	−89
G329.339+00.148	16:00:33.12	−52:44:39.8	160	Y	13	8.8	86	110	Y	9.3	6.8	−85
G329.341−00.644	16:04:01.70	−53:20:21.1	0.15	N	13	8.8	88	0.34	N	9.3	6.7	−87
G329.407−00.459	16:03:32.64	−53:09:27	2.8	Y	13	8.8	89	2.2	−	9.4	6.8	−85

Table 7.4 – continued from previous page

Field name	RA		Dec. (J2000) (d:m:s)	Low Resolution			High Resolution					
	(J2000) (h:m:s)	(J2000) (d:m:s)		rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)	Position angle (°)	rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)
G326.323−00.393	15:47:04.58	−55:04:50.5	0.23	N	11	8.4	−82	0.37	N	7.9	6.3	−84
G326.448−00.748	15:49:18.62	−55:16:51.6	0.58	Y	11	8.4	−81	0.57	Y	7.8	6.3	−85
G326.608+00.799	15:43:36	−53:57:47.1	1.2	N	10	8.7	−76	0.56	N	7.8	6.3	−83
G326.641+00.611	15:44:33.33	−54:05:31.5	52	N	10	8.7	−74	21	N	7.8	6.3	−85
G326.662+00.520	15:45:02.95	−54:09:03.2	7	Y	10	8.6	−76	6.1	−	7.8	6.3	−84
G326.859−00.677	15:51:14.18	−54:58:04.8	0.19	N	10	8.6	−76	0.35	N	7.9	6.3	−85
G327.120+00.511	15:47:32.73	−53:52:38.2	0.65	N	9.6	8.7	−80	0.44	N	7.3	6.4	84
G327.291−00.578	15:53:07.65	−54:37:06.2	110	N	9.9	8.5	86	37	N	7.4	6.5	80
G327.395+00.197	15:50:20.06	−53:57:07.5	0.14	N	9.7	8.7	−86	0.19	N	7.3	6.4	78
G327.566−00.850	15:55:47.61	−54:39:11.5	1.5	N	9.6	8.6	−86	0.8	N	7.4	6.5	86
G327.590−00.094	15:52:36.81	−54:03:18.7	0.13	N	9.7	8.6	89	0.17	N	7.3	6.4	74
G327.618−00.111	15:52:50.20	−54:03:00.7	0.2	N	9.7	8.6	89	0.2	N	7.4	6.4	72
G327.710−00.394	15:54:32.97	−54:12:36.3	4.9	N	9.6	8.6	84	1.7	N	7.4	6.4	72
G327.808−00.634	15:56:06.91	−54:19:54.4	0.33	N	9.6	8.5	82	0.22	N	7.3	6.5	68
G327.945−00.115	15:54:33.91	−53:50:44.1	0.63	N	9.5	8.8	73	0.4	N	7.2	6.5	82
G328.140−00.432	15:56:57.74	−53:57:48.6	0.12	N	9.5	8.7	75	0.17	N	7.2	6.5	82
G328.164+00.587	15:52:42.36	−53:09:50.4	0.39	Y	9.5	8.7	73	0.31	Y	7.1	6.4	73
G328.237−00.547	15:57:58.27	−53:59:22.5	2.3	Y	9.4	8.5	78	1.8	Y	7.2	6.4	77
G328.254−00.532	15:57:59.76	−53:58:00.4	1.6	N	9.5	8.6	80	1	N	7.1	6.4	75
G328.809+00.633	15:55:48.69	−52:43:05.5	130	Y	13	8.8	84	96	Y	9.6	6.5	88
G328.942+00.565	15:56:46.17	−52:41:04.9	6	Y	13	8.9	84	3.2	−	9.5	6.5	89
G329.031−00.198	16:00:30.31	−53:12:27.3	0.23	N	13	8.7	82	0.39	N	9.6	6.6	89
G329.066−00.308	16:01:09.93	−53:16:02.6	0.14	N	13	8.8	84	0.33	N	9.5	6.6	−89
G329.183−00.314	16:01:47.01	−53:11:43.4	0.42	Y	13	8.9	85	0.47	Y	9.5	6.4	−86
G329.272+00.115	16:00:21.76	−52:48:48.2	4.1	Y	13	8.8	84	1.6	Y	9.3	6.7	−89
G329.339+00.148	16:00:33.12	−52:44:39.8	160	Y	13	8.8	86	110	Y	9.3	6.8	−85
G329.341−00.644	16:04:01.70	−53:20:21.1	0.15	N	13	8.8	88	0.34	N	9.3	6.7	−87
G329.407−00.459	16:03:32.64	−53:09:27	2.8	Y	13	8.8	89	2.2	−	9.4	6.8	−85

Table 7.4 – continued from previous page

Field name	RA		Dec. (J2000) (d:m:s)	Low Resolution			High Resolution					
	(J2000) (h:m:s)	(J2000) (d:m:s)		rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)	Position angle (°)	rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)
G329.469+00.503	15:59:40.70	-52:23:27.2	0.46	N	13	8.8	89	0.33	N	9.5	6.5	-86
G329.610+00.114	16:02:03.14	-52:35:33.3	0.24	Y	13	8.8	89	0.31	Y	9.5	6.5	-85
G329.622+00.138	16:02:00.28	-52:33:59.4	0.24	N	13	8.9	-88	0.29	N	9.6	6.4	-90
G329.719+01.164	15:58:07.08	-51:43:32.5	0.19	N	13	8.9	-85	0.31	N	9.4	6.5	-82
G330.070+01.064	16:00:15.43	-51:34:25.6	0.18	N	9.7	8.8	77	0.23	N	7.4	6.4	-87
G330.226+00.290	16:04:18.93	-52:03:12.9	0.13	N	9.6	8.9	76	0.16	N	7.4	6.3	-87
G330.283+00.493	16:03:43.05	-51:51:48.2	2.6	Y	9.7	8.9	79	2	Y	7.4	6.4	-86
G330.875-00.383	16:10:23.08	-52:06:58.6	2.6	N	10	8.3	-90	25	N	7.2	6.4	-87
G330.878-00.367	16:10:19.8	-52:06:07.9	52	Y	9.6	8.9	76	43	-	7.4	6.2	-87
G330.953-00.182	16:09:52.36	-51:54:57.6	190	Y	9.7	8.8	82	220	Y	7.3	6.4	-88
G331.120-00.118	16:10:23.04	-51:45:20.5	0.39	N	9.7	9	-85	0.26	N	7.1	6.6	87
G331.134+00.156	16:09:15.16	-51:32:38.7	3.2	N	9.8	8.9	78	1.3	N	7	6.7	-80
G331.437-00.304	16:12:42	-51:40:30.7	3.2	N	10	8.6	-81	0.28	N	7	6.6	-87
G332.351-00.436	16:17:31.51	-51:08:21.8	0.71	N	9.8	8.9	82	0.33	N	7.1	6.6	-82
G332.364+00.607	16:13:01.46	-50:22:36.8	0.2	N	9.8	8.8	68	0.18	N	7.2	6.2	72
G332.987-00.487	16:20:37.8	-50:43:49.8	4	N	10	8.8	73	1.4	N	7.2	6.6	90
G333.029-00.015	16:18:44.16	-50:21:50.7	0.3	N	9.9	8.6	70	0.2	N	7.2	6.3	70
G333.130-00.560	16:21:35.73	-50:40:50.8	1.1	N	9.9	8.7	71	0.62	N	7.2	6.3	75
G333.184-00.091	16:19:45.62	-50:18:34.9	5	N	9.6	8.7	73	2.1	N	7.2	6.2	69
G333.234-00.062	16:19:51.26	-50:15:14.7	0.43	N	9.5	8.7	72	0.31	N	7	6.3	80
G333.315+00.105	16:19:29.01	-50:04:41.1	0.45	Y	9.7	8.7	73	0.28	-	7	6.3	85
G333.387+00.032	16:20:07.58	-50:04:47.2	0.53	Y	9.6	8.7	78	0.42	Y	7.1	6.3	81
G333.466-00.164	16:21:20.18	-50:09:48.6	22	Y	9.5	8.7	87	12	-	7.1	6.5	78
G333.562-00.025	16:21:08.80	-49:59:48.1	0.57	N	9.6	8.6	85	0.71	N	7.1	6.5	85
G333.646+00.058	16:21:09.14	-49:52:45.8	0.3	N	9.4	8.6	-86	0.23	N	6.8	6.4	86
G333.683-00.437	16:23:29.78	-50:12:08.6	5.2	Y	9.4	8.7	-84	4.2	-	6.9	6.4	84
G333.761-00.226	16:22:54.26	-49:59:54.6	2.9	N	9.2	8.8	88	0.29	N	6.8	6.4	75
G333.851+00.527	16:20:00.91	-49:24:06.8	0.17	N	9.3	8.5	87	0.17	N	7	6.2	78

Table 7.4 – continued from previous page

Field name	RA		Dec. (J2000) (d:m:s)	Low Resolution				High Resolution				
	(J2000) (h:m:s)	(J2000) (d:m:s)		rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)	Position angle (°)	rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)
G333.900−00.099	16:22:57.38	−49:48:34.9	0.16	N	9.3	8.5	−88	0.22	N	7	6.2	78
G333.931−00.135	16:23:14.83	−49:48:48.9	0.35	N	9.3	8.6	−88	0.29	N	7	6.2	76
G334.138−00.023	16:23:39.55	−49:35:15.3	0.21	N	10	8.4	−89	0.35	N	7.9	6.1	88
G334.307−00.079	16:24:38.11	−49:30:24.4	0.19	N	11	8.3	−87	0.38	N	7.9	6.2	88
G334.635−00.015	16:25:45.72	−49:13:37.5	0.59	N	11	8.3	−88	0.49	N	7.9	6.2	−90
G334.935−00.098	16:27:24.24	−49:04:11.2	0.21	N	11	8.3	−86	0.39	N	7.9	6.2	−90
G335.060−00.427	16:29:23.13	−49:12:27	0.19	Y	10	8.3	−86	0.36	Y	7.8	6.2	−89
G335.426−00.240	16:30:05.56	−48:48:44.6	0.22	N	10	8.3	−84	0.34	N	7.8	6.1	−88
G335.556−00.307	16:30:55.96	−48:45:50.0	0.15	N	10	8.3	−83	0.37	N	7.7	6.1	89
G335.585−00.290	16:30:58.8	−48:43:53.4	0.21	Y	11	8.1	−84	0.41	Y	7.6	6.1	−88
G335.726+00.191	16:29:27.36	−48:17:53.1	0.22	N	10	8	−85	0.36	N	7.8	6.1	−86
G335.789+00.174	16:29:47.32	−48:15:51.8	0.26	Y	10	8.1	−83	0.22	Y	7.8	6.1	−88
G335.824−00.177	16:31:28.32	−48:28:49.0	0.19	N	10	8.2	−82	0.29	N	7.8	6.1	−88
G336.018−00.827	16:35:09.26	−48:46:47.2	6.8	N	10	8.1	−83	4	N	7.9	6	−89
G336.358−00.137	16:33:29.16	−48:03:43.9	19	Y	10	8.1	−81	12	−	7.8	5.9	86
G336.409−00.257	16:34:13.2	−48:06:20.8	5.7	Y	10	8.2	−81	2.8	Y	7.9	6	86
G336.433−00.262	16:34:20.20	−48:05:32.2	4	N	10	8.3	−85	3.3	N	7.8	6.1	89
G336.464−00.157	16:34:00.04	−47:59:53.5	1.3	N	10	8.2	−87	0.88	N	7.8	6.2	−87
G336.496−00.271	16:34:38.01	−48:03:03.9	3.7	N	10	8.2	−87	3.2	N	7.8	6.2	−89
G336.526−00.156	16:34:15	−47:57:07.5	1.4	N	10	8.1	−87	0.99	N	7.7	6.2	89
G336.703−00.099	16:34:42.76	−47:46:57.7	0.44	N	10	8.2	−87	0.5	N	7.8	6.3	88
G336.809+00.119	16:34:11.11	−47:33:25.2	1.9	N	10	8.3	−87	0.8	N	7.8	6.1	90
G336.822+00.028	16:34:38.28	−47:36:32.0	11	Y	10	8.3	−86	6	Y	7.7	6.2	−90
G336.825+00.139	16:34:09.81	−47:31:53.0	0.91	N	10	8.2	−88	0.58	N	7.7	6	−90
G336.830−00.375	16:36:26.18	−47:52:31.0	0.19	N	10	8.2	−87	0.36	N	7.7	6	−88
G336.864+00.005	16:34:54.43	−47:35:37.3	7.1	N	10	8.2	−86	4	N	7.6	6.1	−87
G336.881+00.008	16:34:57.64	−47:34:46.5	8.2	N	10	8.3	−86	3.3	N	7.7	6	−85
G336.881+00.008	16:34:57.64	−47:34:46.5	8.2	N	10	8.3	−86	3.3	N	7.7	6	−85

Table 7.4 – continued from previous page

Field name	RA		Dec. (J2000) (d:m:s)	Low Resolution			High Resolution					
	(J2000) (h:m:s)	(J2000) (d:m:s)		rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)	Position angle ($^{\circ}$)	rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)
G333.900−00.099	16:22:57.38	−49:48:34.9	0.16	N	9.3	8.5	−88	0.22	N	7	6.2	78
G333.931−00.135	16:23:14.83	−49:48:48.9	0.35	N	9.3	8.6	−88	0.29	N	7	6.2	76
G334.138−00.023	16:23:39.55	−49:35:15.3	0.21	N	10	8.4	−89	0.35	N	7.9	6.1	88
G334.307−00.079	16:24:38.11	−49:30:24.4	0.19	N	11	8.3	−87	0.38	N	7.9	6.2	88
G334.635−00.015	16:25:45.72	−49:13:37.5	0.59	N	11	8.3	−88	0.49	N	7.9	6.2	−90
G334.935−00.098	16:27:24.24	−49:04:11.2	0.21	N	11	8.3	−86	0.39	N	7.9	6.2	−90
G335.060−00.427	16:29:23.13	−49:12:27	0.19	Y	10	8.3	−86	0.36	Y	7.8	6.2	−89
G335.426−00.240	16:30:05.56	−48:48:44.6	0.22	N	10	8.3	−84	0.34	N	7.8	6.1	−88
G335.556−00.307	16:30:55.96	−48:45:50.0	0.15	N	10	8.3	−83	0.37	N	7.7	6.1	89
G335.585−00.290	16:30:58.8	−48:43:53.4	0.21	Y	11	8.1	−84	0.41	Y	7.6	6.1	−88
G335.726+00.191	16:29:27.36	−48:17:53.1	0.22	N	10	8	−85	0.36	N	7.8	6.1	−86
G335.789+00.174	16:29:47.32	−48:15:51.8	0.26	Y	10	8.1	−83	0.22	Y	7.8	6.1	−88
G335.824−00.177	16:31:28.32	−48:28:49.0	0.19	N	10	8.2	−82	0.29	N	7.8	6.1	−88
G336.018−00.827	16:35:09.26	−48:46:47.2	6.8	N	10	8.1	−83	4	N	7.9	6	−89
G336.358−00.137	16:33:29.16	−48:03:43.9	19	Y	10	8.1	−81	12	−	7.8	5.9	86
G336.409−00.257	16:34:13.2	−48:06:20.8	5.7	Y	10	8.2	−81	2.8	Y	7.9	6	86
G336.433−00.262	16:34:20.20	−48:05:32.2	4	N	10	8.3	−85	3.3	N	7.8	6.1	89
G336.464−00.157	16:34:00.04	−47:59:53.5	1.3	N	10	8.2	−87	0.88	N	7.8	6.2	−87
G336.496−00.271	16:34:38.01	−48:03:03.9	3.7	N	10	8.2	−87	3.2	N	7.8	6.2	−89
G336.526−00.156	16:34:15	−47:57:07.5	1.4	N	10	8.1	−87	0.99	N	7.7	6.2	89
G336.703−00.099	16:34:42.76	−47:46:57.7	0.44	N	10	8.2	−87	0.5	N	7.8	6.3	88
G336.809+00.119	16:34:11.11	−47:33:25.2	1.9	N	10	8.3	−87	0.8	N	7.8	6.1	90
G336.822+00.028	16:34:38.28	−47:36:32.0	11	Y	10	8.3	−86	6	Y	7.7	6.2	−90
G336.825+00.139	16:34:09.81	−47:31:53.0	0.91	N	10	8.2	−88	0.58	N	7.7	6	−90
G336.830−00.375	16:36:26.18	−47:52:31.0	0.19	N	10	8.2	−87	0.36	N	7.7	6	−88
G336.864+00.005	16:34:54.43	−47:35:37.3	7.1	N	10	8.2	−86	4	N	7.6	6.1	−87
G336.881+00.008	16:34:57.64	−47:34:46.5	8.2	N	10	8.3	−86	3.3	N	7.7	6	−85
G336.916−00.024	16:35:14.28	−47:34:30	8.6	N	10	8.1	−86	6.5	N	7.8	5.9	−83

Table 7.4 – continued from previous page

Field name	RA		Dec. (J2000) (d:m:s)	Low Resolution			High Resolution					
	(J2000) (h:m:s)	(J2000) (d:m:s)		rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)	Position angle (°)	rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)
G336.941−00.156	16:35:55.2	−47:38:45.2	2.9	N	10	8.1	−85	1.2	N	7.8	6	−83
G336.957−00.225	16:36:16.99	−47:40:48.7	0.36	N	9.1	8.1	68	0.21	N	7	5.8	69
G336.958−00.977	16:39:37.56	−48:10:58.4	0.11	N	9.1	8.2	69	0.15	N	6.9	5.9	67
G337.052−00.226	16:36:40.17	−47:36:38.5	1.1	N	9.3	7.9	72	0.33	N	7	5.8	69
G337.097−00.929	16:39:57.76	−48:02:49.2	0.17	Y	9.3	7.9	72	0.2	Y	7	5.8	68
G337.132−00.068	16:36:17.66	−47:26:40.9	0.6	N	9.2	7.9	73	0.35	N	7.1	5.9	63
G337.153−00.395	16:37:48.86	−47:38:56.4	0.12	N	9.3	7.9	73	0.15	N	7.1	5.8	65
G337.176−00.032	16:36:18.81	−47:23:20.0	2.9	N	9.4	8	74	1.2	N	7.2	5.8	69
G337.201+00.114	16:35:46.56	−47:16:16.6	0.41	N	9.5	8	72	0.33	N	7.1	5.8	68
G337.202−00.094	16:36:41.23	−47:24:40.3	2.2	N	9.6	8	73	0.98	N	7.1	5.8	68
G333.900−00.099	16:22:57.38	−49:48:34.9	0.16	N	9.3	8.5	−88	0.22	N	7	6.2	78
G333.931−00.135	16:23:14.83	−49:48:48.9	0.35	N	9.3	8.6	−88	0.29	N	7	6.2	76
G334.138−00.023	16:23:39.55	−49:35:15.3	0.21	N	10	8.4	−89	0.35	N	7.9	6.1	88
G334.307−00.079	16:24:38.11	−49:30:24.4	0.19	N	11	8.3	−87	0.38	N	7.9	6.2	88
G334.635−00.015	16:25:45.72	−49:13:37.5	0.59	N	11	8.3	−88	0.49	N	7.9	6.2	−90
G334.935−00.098	16:27:24.24	−49:04:11.2	0.21	N	11	8.3	−86	0.39	N	7.9	6.2	−90
G335.060−00.427	16:29:23.13	−49:12:27	0.19	Y	10	8.3	−86	0.36	Y	7.8	6.2	−89
G335.426−00.240	16:30:05.56	−48:48:44.6	0.22	N	10	8.3	−84	0.34	N	7.8	6.1	−88
G335.556−00.307	16:30:55.96	−48:45:50.0	0.15	N	10	8.3	−83	0.37	N	7.7	6.1	89
G335.585−00.290	16:30:58.8	−48:43:53.4	0.21	Y	11	8.1	−84	0.41	Y	7.6	6.1	−88
G335.726+00.191	16:29:27.36	−48:17:53.1	0.22	N	10	8	−85	0.36	N	7.8	6.1	−86
G335.789+00.174	16:29:47.32	−48:15:51.8	0.26	Y	10	8.1	−83	0.22	Y	7.8	6.1	−88
G335.824−00.177	16:31:28.32	−48:28:49.0	0.19	N	10	8.2	−82	0.29	N	7.8	6.1	−88
G336.018−00.827	16:35:09.26	−48:46:47.2	6.8	N	10	8.1	−83	4	N	7.9	6	−89
G336.358−00.137	16:33:29.16	−48:03:43.9	19	Y	10	8.1	−81	12	−	7.8	5.9	86
G336.409−00.257	16:34:13.2	−48:06:20.8	5.7	Y	10	8.2	−81	2.8	Y	7.9	6	86
G336.433−00.262	16:34:20.20	−48:05:32.2	4	N	10	8.3	−85	3.3	N	7.8	6.1	89
G336.464−00.157	16:34:00.04	−47:59:53.5	1.3	N	10	8.2	−87	0.88	N	7.8	6.2	−87

Table 7.4 – continued from previous page

Field name	RA		Dec. (J2000) (d:m:s)	Low Resolution			High Resolution					
	(J2000) (h:m:s)	(J2000) (d:m:s)		rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)	Position angle (°)	rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)
G336.496−00.271	16:34:38.01	−48:03:03.9	3.7	N	10	8.2	−87	3.2	N	7.8	6.2	−89
G336.526−00.156	16:34:15	−47:57:07.5	1.4	N	10	8.1	−87	0.99	N	7.7	6.2	89
G336.703−00.099	16:34:42.76	−47:46:57.7	0.44	N	10	8.2	−87	0.5	N	7.8	6.3	88
G336.809+00.119	16:34:11.11	−47:33:25.2	1.9	N	10	8.3	−87	0.8	N	7.8	6.1	90
G336.822+00.028	16:34:38.28	−47:36:32.0	11	Y	10	8.3	−86	6	Y	7.7	6.2	−90
G336.825+00.139	16:34:09.81	−47:31:53.0	0.91	N	10	8.2	−88	0.58	N	7.7	6	−90
G336.830−00.375	16:36:26.18	−47:52:31.0	0.19	N	10	8.2	−87	0.36	N	7.7	6	−88
G336.864+00.005	16:34:54.43	−47:35:37.3	7.1	N	10	8.2	−86	4	N	7.6	6.1	−87
G336.881+00.008	16:34:57.64	−47:34:46.5	8.2	N	10	8.3	−86	3.3	N	7.7	6	−85
G336.916−00.024	16:35:14.28	−47:34:30	8.6	N	10	8.1	−86	6.5	N	7.8	5.9	−83
G336.941−00.156	16:35:55.2	−47:38:45.2	2.9	N	10	8.1	−85	1.2	N	7.8	6	−83
G336.957−00.225	16:36:16.99	−47:40:48.7	0.36	N	9.1	8.1	68	0.21	N	7	5.8	69
G336.958−00.977	16:39:37.56	−48:10:58.4	0.11	N	9.1	8.2	69	0.15	N	6.9	5.9	67
G336.941−00.156	16:35:55.2	−47:38:45.2	2.9	N	10	8.1	−85	1.2	N	7.8	6	−83
G336.957−00.225	16:36:16.99	−47:40:48.7	0.36	N	9.1	8.1	68	0.21	N	7	5.8	69
G336.958−00.977	16:39:37.56	−48:10:58.4	0.11	N	9.1	8.2	69	0.15	N	6.9	5.9	67
G337.052−00.226	16:36:40.17	−47:36:38.5	1.1	N	9.3	7.9	72	0.33	N	7	5.8	69
G337.097−00.929	16:39:57.76	−48:02:49.2	0.17	Y	9.3	7.9	72	0.2	Y	7	5.8	68
G337.132−00.068	16:36:17.66	−47:26:40.9	0.6	N	9.2	7.9	73	0.35	N	7.1	5.9	63
G337.153−00.395	16:37:48.86	−47:38:56.4	0.12	N	9.3	7.9	73	0.15	N	7.1	5.8	65
G337.176−00.032	16:36:18.81	−47:23:20.0	2.9	N	9.4	8	74	1.2	N	7.2	5.8	69
G337.201+00.114	16:35:46.56	−47:16:16.6	0.41	N	9.5	8	72	0.33	N	7.1	5.8	68
G337.202−00.094	16:36:41.23	−47:24:40.3	2.2	N	9.6	8	73	0.98	N	7.1	5.8	68
G333.900−00.099	16:22:57.38	−49:48:34.9	0.16	N	9.3	8.5	−88	0.22	N	7	6.2	78
G333.931−00.135	16:23:14.83	−49:48:48.9	0.35	N	9.3	8.6	−88	0.29	N	7	6.2	76
G334.138−00.023	16:23:39.55	−49:35:15.3	0.21	N	10	8.4	−89	0.35	N	7.9	6.1	88
G334.307−00.079	16:24:38.11	−49:30:24.4	0.19	N	11	8.3	−87	0.38	N	7.9	6.2	88
G334.635−00.015	16:25:45.72	−49:13:37.5	0.59	N	11	8.3	−88	0.49	N	7.9	6.2	−90

Table 7.4 – continued from previous page

Field name	RA		Dec. (J2000) (d:m:s)	Low Resolution			High Resolution					
	(J2000) (h:m:s)	(J2000) (d:m:s)		rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)	Position angle (°)	rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)
G334.935−00.098	16:27:24.24	−49:04:11.2	0.21	N	11	8.3	−86	0.39	N	7.9	6.2	−90
G335.060−00.427	16:29:23.13	−49:12:27	0.19	Y	10	8.3	−86	0.36	Y	7.8	6.2	−89
G335.426−00.240	16:30:05.56	−48:48:44.6	0.22	N	10	8.3	−84	0.34	N	7.8	6.1	−88
G335.556−00.307	16:30:55.96	−48:45:50.0	0.15	N	10	8.3	−83	0.37	N	7.7	6.1	89
G335.585−00.290	16:30:58.8	−48:43:53.4	0.21	Y	11	8.1	−84	0.41	Y	7.6	6.1	−88
G335.726+00.191	16:29:27.36	−48:17:53.1	0.22	N	10	8	−85	0.36	N	7.8	6.1	−86
G335.789+00.174	16:29:47.32	−48:15:51.8	0.26	Y	10	8.1	−83	0.22	Y	7.8	6.1	−88
G335.824−00.177	16:31:28.32	−48:28:49.0	0.19	N	10	8.2	−82	0.29	N	7.8	6.1	−88
G336.018−00.827	16:35:09.26	−48:46:47.2	6.8	N	10	8.1	−83	4	N	7.9	6	−89
G336.358−00.137	16:33:29.16	−48:03:43.9	19	Y	10	8.1	−81	12	−	7.8	5.9	86
G336.409−00.257	16:34:13.2	−48:06:20.8	5.7	Y	10	8.2	−81	2.8	Y	7.9	6	86
G336.433−00.262	16:34:20.20	−48:05:32.2	4	N	10	8.3	−85	3.3	N	7.8	6.1	89
G336.464−00.157	16:34:00.04	−47:59:53.5	1.3	N	10	8.2	−87	0.88	N	7.8	6.2	−87
G336.496−00.271	16:34:38.01	−48:03:03.9	3.7	N	10	8.2	−87	3.2	N	7.8	6.2	−89
G336.526−00.156	16:34:15	−47:57:07.5	1.4	N	10	8.1	−87	0.99	N	7.7	6.2	89
G336.703−00.099	16:34:42.76	−47:46:57.7	0.44	N	10	8.2	−87	0.5	N	7.8	6.3	88
G336.809+00.119	16:34:11.11	−47:33:25.2	1.9	N	10	8.3	−87	0.8	N	7.8	6.1	90
G336.822+00.028	16:34:38.28	−47:36:32.0	11	Y	10	8.3	−86	6	Y	7.7	6.2	−90
G336.825+00.139	16:34:09.81	−47:31:53.0	0.91	N	10	8.2	−88	0.58	N	7.7	6	−90
G336.830−00.375	16:36:26.18	−47:52:31.0	0.19	N	10	8.2	−87	0.36	N	7.7	6	−88
G336.864+00.005	16:34:54.43	−47:35:37.3	7.1	N	10	8.2	−86	4	N	7.6	6.1	−87
G336.881+00.008	16:34:57.64	−47:34:46.5	8.2	N	10	8.3	−86	3.3	N	7.7	6	−85
G336.916−00.024	16:35:14.28	−47:34:30	8.6	N	10	8.1	−86	6.5	N	7.8	5.9	−83
G336.941−00.156	16:35:55.2	−47:38:45.2	2.9	N	10	8.1	−85	1.2	N	7.8	6	−83
G336.957−00.225	16:36:16.99	−47:40:48.7	0.36	N	9.1	8.1	68	0.21	N	7	5.8	69
G336.958−00.977	16:39:37.56	−48:10:58.4	0.11	N	9.1	8.2	69	0.15	N	6.9	5.9	67
G337.052−00.226	16:36:40.17	−47:36:38.5	1.1	N	9.3	7.9	72	0.33	N	7	5.8	69
G337.097−00.929	16:39:57.76	−48:02:49.2	0.17	Y	9.3	7.9	72	0.2	Y	7	5.8	68

Table 7.4 – continued from previous page

Field name	RA		Dec. (J2000) (d:m:s)	Low Resolution			High Resolution					
	(J2000) (h:m:s)	(J2000) (d:m:s)		rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)	Position angle (°)	rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)
G337.132−00.068	16:36:17.66	−47:26:40.9	0.6	N	9.2	7.9	73	0.35	N	7.1	5.9	63
G337.153−00.395	16:37:48.86	−47:38:56.4	0.12	N	9.3	7.9	73	0.15	N	7.1	5.8	65
G337.176−00.032	16:36:18.81	−47:23:20.0	2.9	N	9.4	8	74	1.2	N	7.2	5.8	69
G337.201+00.114	16:35:46.56	−47:16:16.6	0.41	N	9.5	8	72	0.33	N	7.1	5.8	68
G337.202−00.094	16:36:41.23	−47:24:40.3	2.2	N	9.6	8	73	0.98	N	7.1	5.8	68
G337.258−00.101	16:36:56.32	−47:22:26.4	1.8	N	9.7	8.1	72	0.55	N	7	5.8	69
G337.263−00.070	16:36:49.36	−47:20:58.5	0.76	N	9.6	7.9	76	0.34	N	6.9	5.9	69
G337.388−00.210	16:37:56.01	−47:21:01.0	0.17	N	9.5	8	75	0.18	N	7	5.9	69
G337.404−00.402	16:38:50.52	−47:28:00.1	9	Y	9.6	8	68	6.4	−	7.1	5.8	71
G337.613−00.060	16:38:09.52	−47:04:59.8	10	Y	9.6	7.9	67	6	−	7.1	5.8	72
G337.632−00.079	16:38:19.12	−47:04:53.4	5.5	Y	9.7	7.9	68	3	−	7.1	5.7	71
G337.686+00.137	16:37:35.42	−46:53:47.7	0.36	N	9.7	7.8	69	0.24	N	7.1	5.7	74
G337.705−00.053	16:38:29.64	−47:00:35.6	18	Y	9.7	7.8	69	15	Y	7	5.8	70
G337.710+00.089	16:37:53.4	−46:54:40.6	14	Y	9.6	7.9	74	9.8	Y	7.1	5.8	77
G337.720+00.065	16:38:02.20	−46:55:13.4	6.4	N	9.5	7.9	74	3.1	N	7.1	5.9	76
G337.844−00.375	16:40:26.66	−47:07:13.4	3	Y	9.5	7.9	76	2.1	Y	7.2	6	75
G337.920−00.456	16:41:06.04	−47:07:02.6	77	Y	9.6	7.8	73	49	−	7.4	5.9	75
G337.966−00.169	16:40:01.08	−46:53:34.4	0.62	N	9.6	7.9	74	0.3	N	7.4	5.9	68
G337.997+00.136	16:38:48.50	−46:39:57.6	0.28	N	9.6	7.9	73	0.26	N	7.4	5.9	69
G338.075+00.012	16:39:39.04	−46:41:27.9	69	Y	9.8	7.9	78	45	Y	7.3	5.8	71
G338.140+00.178	16:39:10.92	−46:31:55.2	0.21	N	9.8	8	78	0.17	N	7.4	5.8	76
G338.160−00.064	16:40:18.69	−46:40:37.9	0.45	N	9.7	8	77	0.28	N	7.4	5.8	75
G338.287+00.120	16:40:00.12	−46:27:37.0	2.4	N	11	8.8	−85	0.69	N	8.4	6.6	−84
G338.325−00.409	16:42:27.52	−46:46:54.1	0.18	N	11	8.8	−83	0.29	N	8.3	6.6	−84
G338.388+00.162	16:40:12.36	−46:21:25.5	8.1	Y	11	9	−83	4.8	−	8.4	6.5	−83
G338.392−00.403	16:42:41.28	−46:43:39	0.15	N	11	8.9	−83	0.29	N	8.3	6.5	−81
G338.396−00.007	16:40:58.41	−46:27:47.8	5.6	N	11	8.9	−84	1.6	N	8.4	6.5	−83
G338.432+00.058	16:40:49.8	−46:23:36.9	59	Y	11	8.8	−84	38	−	8.5	6.4	−85

Table 7.4 – continued from previous page

Field name	RA		Dec. (J2000) (d:m:s)	Low Resolution			High Resolution					
	(J2000) (h:m:s)	(J2000) (d:m:s)		rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)	Position angle (°)	rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)
G338.497+00.207	16:40:25.89	-46:14:43.4	1.1	N	11	8.7	-85	0.69	N	8.4	6.4	-81
G338.850+00.409	16:40:54.28	-45:50:52.0	2.1	Y	11	8.6	-79	1.7	-	8.3	6.5	-72
G338.875-00.084	16:43:08.25	-46:09:12.9	0.6	N	11	8.6	-79	1.2	N	8.3	6.5	-73
G338.902+00.394	16:41:10.05	-45:49:05.5	11	N	11	8.6	-79	8	N	8.3	6.4	-80
G338.925+00.557	16:40:33.52	-45:41:36.9	1.4	N	11	8.7	-78	0.88	N	8.2	6.4	-80
G338.925+00.634	16:40:13.56	-45:38:33.3	14	Y	11	8.5	-79	8.9	-	8.2	6.5	-78
G338.935-00.062	16:43:16.00	-46:05:40.2	4.7	N	11	8.5	-82	3.2	N	8.2	6.5	-79
G339.053-00.315	16:44:48.98	-46:10:13.0	0.62	Y	11	8.5	-82	0.53	Y	8.2	6.5	-78
G339.064+00.152	16:42:49.56	-45:51:23.7	0.73	N	11	8.6	-73	0.27	N	8.1	6.4	-69
G339.204-00.018	16:44:05.68	-45:51:43.2	0.17	N	11	8.6	-71	0.23	N	8.1	6.4	-68
G339.282+00.136	16:43:43.10	-45:42:07.9	0.65	Y	11	8.7	-63	0.45	Y	8.1	6.6	-67
G339.476+00.185	16:44:13.8	-45:31:24.9	5.5	Y	11	8.6	-62	3.8	-	8.1	6.5	-71
G339.477+00.043	16:44:50.97	-45:36:56.1	0.28	N	11	8.6	-62	0.29	N	8.1	6.5	-74
G339.582-00.127	16:45:58.82	-45:38:47.0	0.6	N	11	8.7	-61	0.33	N	8.1	6.6	-75
G339.762+00.054	16:45:51.55	-45:23:32.6	0.44	N	11	8.9	-65	0.31	N	8.1	6.7	-75
G339.909+00.240	16:45:36.16	-45:09:36.3	0.18	N	11	8.9	-64	0.26	N	8.1	6.7	-69
G339.949-00.539	16:49:07.96	-45:37:58.8	3.2	N	11	8.9	-66	1.2	N	8.1	6.8	-73
G339.986-00.425	16:48:46.32	-45:31:51.2	0.15	N	11	9	-65	0.19	N	8.1	6.6	-66
G340.034-01.110	16:51:58.08	-45:55:56.6	0.11	N	10	7.7	86	0.36	N	7.8	5.9	80
G340.118-00.021	16:47:30	-45:10:12	0.2	N	11	7.8	84	0.16	N	8	5.7	85
G340.182-00.047	16:47:50.78	-45:08:15.7	0.33	N	11	7.9	85	0.2	N	8.1	5.7	85
G340.249-00.046	16:48:05.18	-45:05:08.5	7.5	Y	11	8	85	5	Y	8.1	5.7	86
G340.249-00.372	16:49:30.07	-45:17:44.5	14	Y	11	8.1	85	9.4	Y	8.1	5.8	86
G340.518-00.152	16:49:31.36	-44:56:54.6	0.15	N	11	8.1	85	0.17	N	8.1	5.8	85
G340.655-00.235	16:50:22.89	-44:53:48.1	0.12	N	11	8.1	85	0.15	N	8.1	5.8	86
G340.970-01.022	16:54:57.31	-45:09:05.0	0.31	Y	11	8	85	0.26	Y	8.1	5.8	85
G341.124-00.361	16:52:36.76	-44:36:52.5	0.18	N	11	7.9	87	0.18	N	8.2	5.9	86
G341.218-00.212	16:52:17.85	-44:26:52.4	4.4	N	11	7.7	-90	2.1	N	8.3	5.9	85

Table 7.4 – continued from previous page

Field name	RA		Dec. (J2000) (d:m:s)	Low Resolution			High Resolution					
	(J2000) (h:m:s)	(J2000) (d:m:s)		rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)	Position angle (°)	rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)
G341.238−00.270	16:52:37.41	−44:28:07.6	0.33	N	11	7.8	−89	0.17	N	8.2	6	83
G341.276+00.062	16:51:19.41	−44:13:44.4	0.12	N	11	7.9	−88	0.16	N	8.3	6	82
G341.367+00.336	16:50:28.22	−43:59:02.0	0.2	N	11	7.9	−88	0.2	N	8.3	6.1	86
G341.973+00.233	16:53:02.97	−43:34:54.8	4.8	Y	11	7.8	−89	3.3	−	8.3	6	86
G341.990−00.103	16:54:32.88	−43:46:51.2	0.14	N	11	7.9	−89	0.16	N	8.3	6	86
G342.251+00.308	16:53:41.85	−43:19:09.8	1.2	N	11	7.7	−86	0.83	N	8.5	5.9	89
G342.338+00.305	16:54:00.72	−43:15:12.2	0.38	N	11	7.7	−86	0.33	N	8.5	5.8	89
G342.368+00.140	16:54:49.15	−43:20:03.4	0.8	N	10	8.1	−87	0.5	N	7.7	5.9	87
G342.446−00.072	16:55:59.92	−43:24:22.3	0.86	N	10	8.1	−87	0.4	N	7.6	6	86
G342.484+00.183	16:55:02.30	−43:12:59.7	0.11	N	10	8.1	−85	0.19	N	7.9	5.8	87
G342.954−00.019	16:57:30.64	−42:58:34.6	0.14	N	10	8.1	−85	0.27	N	7.8	5.8	88
G343.354−00.067	16:59:04.22	−42:41:35.1	7.2	Y	10	8.1	−85	5	−	7.9	5.7	89
G343.502−00.472	17:01:18.40	−42:49:36.8	0.16	N	10	7.9	−84	0.28	N	7.7	5.9	−90
G343.756−00.163	17:00:49.89	−42:26:08.1	0.24	Y	10	7.9	−83	0.34	Y	7.9	5.8	90
G343.929+00.125	17:00:10.92	−42:07:19.2	3.7	Y	11	7.8	−84	2.9	Y	7.9	5.7	−89
G344.227−00.569	17:04:07.77	−42:18:39.6	38	N	11	7.9	−83	20	N	8	5.8	90
G344.421+00.045	17:02:08.76	−41:46:58.4	87	Y	11	7.6	−85	57	−	8	5.8	−87
G344.581−00.024	17:02:57.72	−41:41:53.8	0.75	Y	11	7.7	−86	0.57	Y	8	5.7	−85
G345.003−00.224	17:05:11.23	−41:29:06.7	25	Y	11	7.8	−83	20	Y	8.1	5.7	−84
G345.131−00.174	17:05:23.23	−41:21:10.8	0.19	N	11	7.8	−82	0.29	N	8.2	5.6	−85
G345.198−00.030	17:04:59.49	−41:12:45.7	0.43	Y	11	7.8	−83	0.48	Y	8.1	5.6	−87
G345.407−00.952	17:09:35.42	−41:35:57.1	120	Y	11	7.8	−82	80	Y	8.2	5.5	−85
G345.424−00.951	17:09:38.56	−41:35:04.5	100	N	11	7.9	−81	54	N	8.1	5.6	−87
G345.441+00.205	17:04:46.87	−40:52:37.9	6.3	Y	11	7.9	−81	3.4	−	8.1	5.7	−84
G345.487+00.314	17:04:28.24	−40:46:28.5	190	Y	14	7.8	−76	130	−	11	5.7	−78
G345.498+01.467	16:59:42.84	−40:03:36	3.4	N	15	7.6	−76	2	N	10	5.6	−77
G345.505+00.348	17:04:22.92	−40:44:21.8	36	N	14	7.6	−75	11	N	10	5.7	−79
G345.424−00.951	17:09:38.56	−41:35:04.5	100	N	11	7.9	−81	54	N	8.1	5.6	−87

Table 7.4 – continued from previous page

Field name	RA		Dec. (J2000) (d:m:s)	Low Resolution			High Resolution					
	(J2000) (h:m:s)	(J2000) (d:m:s)		rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)	Position angle (°)	rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)
G345.441+00.205	17:04:46.87	-40:52:37.9	6.3	Y	11	7.9	-81	3.4	-	8.1	5.7	-84
G345.487+00.314	17:04:28.24	-40:46:28.5	190	Y	14	7.8	-76	130	-	11	5.7	-78
G345.498+01.467	16:59:42.84	-40:03:36	3.4	N	15	7.6	-76	2	N	10	5.6	-77
G345.505+00.348	17:04:22.92	-40:44:21.8	36	N	14	7.6	-75	11	N	10	5.7	-79
G345.576-00.225	17:07:01.48	-41:01:43.3	0.17	N	15	7.6	-75	0.17	N	10	5.8	-79
G345.807-00.044	17:06:59.85	-40:44:08.1	0.51	N	15	7.5	-75	0.16	N	10	5.7	-78
G345.824+00.044	17:06:40.70	-40:40:09.8	2.4	Y	15	7.4	-77	1.3	-	11	5.7	-77
G345.985-00.020	17:07:27.57	-40:34:43.6	0.58	N	15	7.4	-77	0.32	N	11	5.6	-77
G346.036+00.048	17:07:20.01	-40:29:48.8	0.34	Y	15	7.5	-77	0.24	-	11	5.5	-77
G346.231+00.119	17:07:39.09	-40:17:53.1	0.12	N	16	7.3	-75	0.2	N	11	5.6	-76
G346.480+00.221	17:08:00.12	-40:02:15.7	0.15	N	16	7.4	-74	0.19	N	11	5.7	-76
G346.481+00.132	17:08:22.72	-40:05:25.4	0.72	Y	16	7.4	-75	0.44	Y	11	5.7	-75
G346.517+00.117	17:08:33.19	-40:04:14.1	4.8	N	15	7.5	-75	1	N	12	5.7	-75
G346.522+00.085	17:08:42.28	-40:05:07.8	32	Y	15	7.6	-74	19	-	12	5.6	-75
G347.230+00.016	17:11:11.18	-39:33:27.3	0.65	N	12	8.7	-67	0.35	N	8.4	6.5	-71
G347.583+00.213	17:11:26.71	-39:09:22.3	10	N	12	8.6	-68	4.5	N	8.4	6.5	-71
G347.628+00.149	17:11:50.92	-39:09:29.1	21	Y	12	8.7	-67	14	Y	8.6	6.3	-73
G347.631+00.211	17:11:36.04	-39:07:06.9	3.6	N	13	8.6	-75	1.8	N	9.4	6.1	-71
G347.817+00.018	17:12:58.05	-39:04:55.9	0.44	N	13	8.6	-75	0.5	N	9.5	6.2	-72
G347.863+00.019	17:13:06.24	-39:02:39.8	19	Y	13	8.4	-74	12	-	9.8	6.1	-72
G347.902+00.052	17:13:05.11	-38:59:35.5	15	N	11	8.4	-71	7	N	8.3	6.3	-74
G348.027+00.106	17:13:14.11	-38:51:38.8	0.28	N	11	8.4	-71	0.73	N	8.4	6.4	-73
G348.195+00.768	17:11:00.19	-38:20:05.6	0.16	N	12	8.3	-71	0.28	N	8.5	6.5	-72
G348.579-00.920	17:19:10.60	-39:00:24.1	0.5	N	11	8.4	-71	0.95	N	8.3	6.4	-74
G348.617-01.162	17:20:18.64	-39:06:50.7	0.44	N	11	8.3	-71	0.86	N	8.4	6.4	-73
G348.654+00.244	17:14:32.37	-38:16:16.6	0.41	N	11	8.5	-70	0.25	N	8.9	6.2	-74
G348.703-01.043	17:20:04.05	-38:58:30.7	140	N	11	8.5	-70	87	N	9	6.3	-75
G348.727-01.037	17:20:06.52	-38:57:09	250	N	12	8.9	-71	160	N	8.8	6.3	-73

Table 7.4 – continued from previous page

Field name	RA		Dec. (J2000) (d:m:s)	Low Resolution				High Resolution				
	(J2000) (h:m:s)	(J2000) (d:m:s)		rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)	Position angle ($^{\circ}$)	rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)
G348.884+00.096	17:15:50.13	-38:10:12.3	0.24	N	11	8.7	-69	0.28	N	8.7	6.5	-77
G348.892-00.180	17:17:00.24	-38:19:28.9	20	Y	11	8.5	-71	16	-	8.8	6.5	-77
G349.067-00.017	17:16:50.73	-38:05:14.2	0.43	N	11	8.4	-74	0.5	N	8.5	6.4	-76
G349.092+00.106	17:16:24.6	-37:59:45.9	4.9	N	11	8.7	-71	3	N	8.5	6.4	-75
G349.151+00.021	17:16:55.87	-37:59:47.7	6.3	N	11	8.6	-71	3.4	N	8.9	6.5	-75
G349.579-00.679	17:21:05.44	-38:02:54.6	0.9	N	11	8.6	-71	0.43	N	8.7	6.5	-75
G349.799+00.108	17:18:27.74	-37:25:03.3	0.9	N	-	-	-	0.68	N	-	-	-
G349.884+00.231	17:18:12.36	-37:16:40.0	0.2	N	12	8.5	-72	0.29	N	8.9	6.5	-70
G350.011-01.342	17:25:06.52	-38:04:00.8	0.47	Y	11	7.8	-86	0.43	Y	8.3	5.7	-85
G350.015+00.433	17:17:45.45	-37:03:11.8	13	Y	11	7.8	-86	9.1	Y	8.2	5.9	-90
G350.105+00.083	17:19:27	-37:10:53.4	78	Y	11	7.9	-88	48	-	8.2	6	89
G350.116+00.084	17:19:28.82	-37:10:18.8	73	N	11	7.9	-89	42	N	8	6.1	87
G350.116+00.220	17:18:55.10	-37:05:38.0	4.7	N	11	7.9	-85	2.4	N	8	5.9	-89
G350.189+00.003	17:20:01.41	-37:09:30.6	10	Y	11	7.9	-85	6.2	-	8.1	5.9	-86
G350.299+00.122	17:19:50.88	-37:00:00	0.67	N	11	7.8	-85	0.26	N	8.1	5.9	-86
G350.340+00.141	17:19:53.42	-36:57:18.7	1.7	Y	11	7.7	-84	0.95	Y	8.2	5.8	-84
G350.344+00.116	17:20:00.02	-36:58:00.1	5.1	Y	11	7.7	-82	2.9	Y	8.2	5.9	-87
G350.356-00.068	17:20:47.54	-37:03:42.1	0.18	Y	11	7.6	-83	0.18	-	8.3	5.8	-85
G350.520-00.350	17:22:25.32	-37:05:13.5	0.15	N	11	7.6	-83	0.17	N	8.3	5.8	-85
G350.686-00.491	17:23:28.63	-37:01:48.7	0.15	N	11	7.6	-81	0.27	N	7.9	5.9	-87
G351.161+00.697	17:19:57.50	-35:57:52.9	6.9	N	11	7.5	-79	2.5	N	8	5.5	-85
G351.242+00.670	17:20:17.83	-35:54:46.0	240	Y	11	7.6	-79	180	-	7.9	5.6	-81
G351.251+00.652	17:20:23.88	-35:54:56.8	240	N	11	7.6	-79	110	N	8	5.7	-81
G351.382-00.181	17:24:09.57	-36:16:49.4	0.19	Y	11	7.6	-78	0.3	Y	8	5.7	-83
G351.417+00.646	17:20:53.18	-35:46:59.1	190	Y	11	7.5	-78	130	-	8.2	5.6	-78
G351.445+00.660	17:20:54.6	-35:45:08.6	87	N	11	7.5	-78	29	N	8.2	5.6	-82
G351.581-00.353	17:25:25.12	-36:12:46.0	58	Y	11	7.5	-78	44	Y	8	5.6	-79
G351.611+00.172	17:23:21.24	-35:53:32.2	58	N	-	-	-	40	N	-	-	-

Table 7.4 – continued from previous page

Field name	RA		Dec. (J2000) (d:m:s)	Low Resolution				High Resolution				
	(J2000) (h:m:s)	(J2000) (d:m:s)		rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)	Position angle (°)	rms (mJy)	Detection	Major (arcsec)	Minor (arcsec)
G351.688+00.171	17:23:34.51	−35:49:46.2	1.5	N	11	7.6	−76	0.5	N	8.1	5.7	−82
G351.775−00.536	17:26:42.57	−36:09:17.6	16	Y	11	7.4	−77	11	−	8.1	5.8	−82
G352.083+00.167	17:24:41.23	−35:30:18.7	1.1	N	15	7.4	−73	0.61	N	12	5.4	−75
G352.111+00.176	17:24:43.56	−35:28:38.2	1.5	N	15	7.5	−74	0.74	N	12	5.4	−73
G352.133−00.944	17:29:22.22	−36:05:00.2	0.18	Y	15	7.5	−74	0.21	Y	11	5.4	−76
G352.517−00.155	17:27:11.35	−35:19:32.5	9	Y	16	7.5	−73	7	Y	12	5.3	−73
G352.525−00.158	17:27:13.41	−35:19:15.6	9	N	16	7.5	−72	7.1	N	12	5.4	−72
G352.584−00.185	17:27:29.56	−35:17:14.6	7.1	N	15	7.5	−72	3.4	N	12	5.5	−73
G352.604−00.225	17:27:42.72	−35:17:34.0	0.55	N	15	7.6	−73	0.27	N	12	5.5	−73
G352.624−01.077	17:31:15.31	−35:44:47.7	0.24	Y	15	7.5	−72	0.25	Y	12	5.6	−73
G352.630−01.067	17:31:13.92	−35:44:08.5	0.21	Y	15	7.8	−73	0.23	Y	12	5.5	−74
G352.855−00.201	17:28:17.59	−35:04:12.7	22	Y	16	7.7	−71	12	−	13	5.6	−72
G353.216−00.249	17:29:27.79	−34:47:47.4	0.66	N	16	7.6	−70	0.36	N	13	5.6	−72
G353.273+00.641	17:26:01.58	−34:15:15.4	6.9	N	17	7.5	−71	3.1	N	13	5.6	−71
G353.363−00.166	17:29:31.39	−34:37:40.4	25	Y	17	7.4	−71	17	Y	13	5.6	−72
G353.370−00.091	17:29:14.28	−34:34:50.1	2.3	N	12	8.5	−71	1.1	N	8.7	6.4	−73
G353.378+00.438	17:27:07.58	−34:16:50.5	3.5	Y	12	8.6	−71	2.4	−	9.1	6.4	−77
G353.410−00.360	17:30:26.18	−34:41:45.6	100	Y	12	8.5	−71	61	Y	9.1	6.5	−74
G353.429−00.090	17:29:23.47	−34:31:50.1	1.4	N	12	8.5	−71	0.44	N	8.9	6.5	−70
G353.464+00.562	17:26:51.52	−34:08:25.8	0.27	N	12	8.4	−68	0.36	N	9	6.3	−67
G353.537−00.091	17:29:41.25	−34:26:28.3	0.6	N	12	8.5	−70	0.32	N	9	6.3	−66
G354.206−00.038	17:31:15	−33:51:15.1	13	Y	12	8.4	−68	7.3	Y	9	6.3	−67
G354.308−00.110	17:31:48.55	−33:48:29.1	0.33	N	12	8.4	−66	0.3	N	8.8	6.3	−65
G354.496+00.083	17:31:31.77	−33:32:44.1	5.2	N	12	8.3	−67	2	N	9.3	6.2	−68
G354.615+00.472	17:30:17.13	−33:13:55.2	9.8	N	12	8.6	−66	2	N	−	−	−
G354.701+00.299	17:31:12.04	−33:15:16.5	22	N	13	8.6	−66	8.7	N	9.4	6.2	−68
G354.724+00.300	17:31:15.55	−33:14:05.6	37	Y	13	8.6	−67	25	Y	9.1	6.4	−68

TABLE 7.5: Extracted source parameters from our detected radio sources at low resolution. Column 1 is the radio name, which is a combination of the Galactic longitudes and latitudes determined by fitting ellipsoidal Gaussians using IMFIT, Columns 2–8 present 18–GHz source parameters and columns 9–15 present 24–GHz source parameters. Col 6–8 and 13–15 are the deconvolved major, minor and position angle, respectively. Sources with – are those for which sizes could not be deconvolved. Sources with a † indicate those with a poor synthesised beam.

18GHz										24GHz					
Radio name	f_{peak} (mJy beam $^{-1}$)	Δf_{peak} (mJy beam $^{-1}$)	f_{int} (mJy)	Δf_{int} (mJy)	Major (arcsec)	Minor (arcsec)	PA ($^{\circ}$)	f_{peak} (mJy beam $^{-1}$)	Δf_{peak} (mJy beam $^{-1}$)	f_{int} (mJy)	Δf_{int} (mJy)	Major (arcsec)	Minor (arcsec)	PA ($^{\circ}$)	
G300.504−0.173	36	0.85	54	2.2	7.8	5.2	8.8	24	0.47	47	2.2	8	6.1	18.6	
G300.969+1.148	500	12	580	30	4.8	2.4	−44.6	490	35	560	79	3.7	1.6	−50	
G301.136−0.225	870	33	1100	84	6.5	0.9	0.4	1000	110	1400	300	6.8	1.5	−4.4	
G302.032−0.061	830	15	970	28	4.7	2.8	−37.6	670	15	840	35	4.2	2.7	−40.1	
G302.033+0.626	0.48	0.052	0.45	0.08	−	−	−	0.84	0.07	0.78	0.1	−	−	−	
G305.199+0.206	110	2	190	11	9.4	5.7	87.1	53	2.2	68	6.2	4.5	2.4	87.9	
G305.215+0.200	130	3.3	240	19	10.2	6	77.7	46	1.2	83	5.8	8	4.1	−65.6	
G305.359+0.151	91	1.9	140	9.4	7.8	4.6	18.7	61	1.6	89	6.4	7.3	0.8	−31.5	
G305.562+0.013	50	3.8	54	8	−	−	−	41	2.5	45	4.5	−	−	−	
G305.798−0.242	9.7	0.44	12	1.2	−	−	−	8.5	0.64	11	1.4	4.2	2.6	−22.2	
G305.800−0.251	19	0.62	29	1.4	6.9	6.2	−82.8	11	0.89	24	3	7.6	7.5	−89.8	
G305.886+0.017	1.1	0.097	3.8	1.5	23.2	6.8	−27.8	1.3	0.1	1.7	0.2	4.2	−	−	
G308.056−0.396	200	7.9	200	12	−	−	−	190	8.7	200	13	−	−	−	
G308.651−0.508	1.9	0.13	2.8	0.28	9.8	3.7	−22.7	2.9	0.38	3.3	0.7	4.3	2.1	−38.2	
G308.918+0.122	290	10	380	19	6.4	4.3	−0.4	230	11	320	22	5.8	4.1	0.8	
G309.384−0.135	2.1	0.3	2.9	0.61	8.7	1.6	53.8	2.5	0.24	3.2	0.47	5.6	1.7	60.6	
G309.920+0.479	920	35	1000	55	4.9	0.8	−42.7	880	49	1000	85	5.3	0.6	−37	
G310.144+0.760	7.7	0.31	11	0.75	10.2	1.8	79.3	7	0.33	9	0.9	−	−	−	
G311.642−0.380	280	4.4	290	7.1	−	−	−	260	6.1	280	12	−	−	−	
G312.307+0.661	40	0.79	41	1.3	−	−	−	39	0.63	40	1.1	1.7	0.7	−50.9	
G312.597+0.047	72	5	86	12	5.2	2.8	−20.8	50	2.6	69	6.4	5.2	3.2	−21.8	
G314.220+0.272	26	1.3	27	2.3	−	−	−	23	1.5	26	2.9	−	−	−	
G316.363−0.363	15	1.7	56	17	22.1	9	−89.3	10	1.9	40	22	17.8	7	57.4	
G318.049+0.086	5.5	0.65	11	2	15.8	4.2	46.3	4.6	0.82	11	3	14.2	2.9	43.8	
G319.163−0.420	350	19	520	42	8.8	5.5	−10.2	230	11	420	30	8.1	5.1	−3.9	

Table 7.5 – continued from previous page

18GHz										24GHz				
Radio name	f_{peak} (mJy beam ⁻¹)	Δf_{peak} (mJy beam ⁻¹)	f_{int} (mJy)	Δf_{int} (mJy)	Major (arcsec)	Minor (arcsec)	PA (°)	f_{peak} (mJy beam ⁻¹)	Δf_{peak} (mJy beam ⁻¹)	f_{int} (mJy)	Δf_{int} (mJy)	Major (arcsec)	Minor (arcsec)	PA (°)
G320.233-0.284	390	5.1	420	8.2	3	2.1	-48.7	340	3.5	370	6.1	2.2	1.5	-27.1
G320.415+0.116	56	4.4	72	13	5.7	4.3	-71	38	2.8	48	9.6	4.3	2.7	-57.9
G320.427+0.103	26	0.45	32	1.4	5.6	2.5	68.6	21	0.58	27	1.9	5.4	2.1	57.3
G320.778+0.242	30	3.9	32	0.89	—	—	—	24	1.4	27	3	2.8	1.8	-42.1
G321.032-0.485	56	3.7	190	26	22.3	8.2	24.3	26	1.6	83	13	18	4.1	36.5
G321.721+1.174	350	30	780	160	11.6	8.6	49.6	160	10	380	52	9.7	6.8	47.1
G322.164+0.623	860	53	2300	310	14.9	8.6	27.4	440	28	1000	190	9.3	6.9	19.3
G322.707-0.329	41	1.4	150	24	19.2	10.9	-5	24	2.5	91	24	14.6	8.9	-12.2
G323.459-0.079	1000	20	1100	30	2.9	1.3	32.9	1000	44	1100	72	2.8	1.2	30
G323.741-0.254	10	1.2	41	11	18.5	12.9	-78.5	4.6	0.29	13	3.5	13.3	5.7	-71
G323.766-1.370	2.1	0.13	2.6	0.33	6.9	0.6	62.4	1.7	0.25	3.2	1.7	9.6	3.5	79.5
G324.923-0.568	440	6.2	500	11	3.8	2.7	-51.9	370	10	450	19	3.7	3	-45.1
G326.448-0.748	9.1	0.12	9.3	0.19	2.2	0.6	74.3	9.1	0.8	9.8	1.3	3.1	0.4	-53.6
G326.662+0.522	42	3.1	110	15	17.5	6.6	59.8	25	1.7	110	22	19.6	7.9	49.7
G328.164+0.586	6	0.3	6.2	0.48	—	—	—	5.4	0.27	6.3	0.45	3.5	1.6	4.6
G328.236-0.548	36	1.7	42	3.1	—	—	—	36	2.4	42	4.1	3.7	2	-87.1
G328.808+0.633	1600	50	1900	83	6	1.8	45.5	1300	57	1700	110	5.3	1.8	42.1
G328.958+0.566	70	6	110	14	10.8	0.7	-8.6	25	2.2	44	6	8.6	4.6	-21.4
G329.183-0.314	4.9	0.4	5.2	0.62	4.3	1	86.2	5.5	0.54	6.3	0.89	—	—	—
G329.272+0.115	16	1.4	17	3	—	—	—	13	1.8	17	3.5	4.7	3.4	48.2
G329.337+0.147	2100	140	2500	240	5.9	2.1	-39.6	1800	63	2200	110	5.3	2.1	-37.6
G329.403-0.458	27	2.6	49	7.1	11.7	6.9	33.2	17	2.1	35	7	9.9	6.8	47.3
G329.610+0.114	1	0.093	1.4	0.22	8.6	1.1	2.9	1.7	0.24	1.6	0.33	—	—	—
G330.284+0.493	43	1.4	44	2.1	1.5	0.4	59.1	33	3.1	36	6.3	2.4	1.3	35.5
G330.879-0.367	410	35	790	100	12	4.7	-7.2	270	49	540	290	9.3	4.8	8.4
G330.954-0.182	4000	25	4100	44	2.4	1.2	35.9	3600	300	4000	570	2.6	1.8	37.8
G333.314+0.104	4.2	0.36	4.7	0.7	—	—	—	2.8	0.078	3.1	0.23	3.1	1.9	79.2
G333.387+0.032	7.7	0.31	7.8	0.47	—	—	—	6.4	0.49	7	0.9	2.7	0.9	-66.7

Table 7.5 – continued from previous page

18GHz										24GHz				
Radio name	f_{peak} (mJy beam ⁻¹)	Δf_{peak} (mJy beam ⁻¹)	f_{int} (mJy)	Δf_{int} (mJy)	Major (arcsec)	Minor (arcsec)	PA (°)	f_{peak} (mJy beam ⁻¹)	Δf_{peak} (mJy beam ⁻¹)	f_{int} (mJy)	Δf_{int} (mJy)	Major (arcsec)	Minor (arcsec)	PA (°)
G333.466−0.164	160	13	370	56	13.3	8.1	62.4	83	6.6	170	30	8.8	5.2	67.9
G333.679−0.435	72	4.3	81	1.9	4	2.6	65.8	50	8.6	61	2	3.7	2.8	64.5
G335.059−0.428	1.3	0.12	1.6	0.24	6.9	1.5	59.3	1.5	0.083	1.9	0.2	—	—	—
G335.585−0.290	1.6	0.22	1.8	0.38	—	—	—	3.2	0.44	4.3	0.94	4.8	3.6	86.4
G335.789+0.174	1.5	0.08	1.9	0.2	6.1	2.3	−40	1.7	0.1	2.2	0.24	4.4	3	−49
G336.360−0.137	190	11	350	31	13.5	3.6	−82.5	120	7.2	250	23	11.8	2.6	−82.1
G336.410−0.258	33	3.4	27	4.6	—	—	—	31	3.4	35	5.8	—	—	—
G336.823+0.028	110	7.1	120	12	3.8	0.2	18.5	90	10	100	17	3.1	2.5	−54.9
G337.097−0.929	1.8	0.15	1.7	0.2	—	—	—	1.8	0.3	2.1	0.51	—	—	—
G337.404−0.402	160	3.5	160	5.1	1.9	0.1	−81.5	160	2.2	160	3.2	1.3	0.5	52.9
G337.618−0.061	78	2	100	8	6.9	3.3	−89.2	39	2.5	57	11	5.9	2.5	−75.8
G337.632−0.078	55	10	53	15	—	—	—	49	3.7	50	5.5	—	—	—
G337.705−0.053	290	38	290	54	—	—	—	310	20	310	28	—	—	—
G337.708+0.094	150	3	190	8.7	5.7	2.6	10.7	98	2.4	160	8.8	6.1	3.7	1.8
G337.711+0.085	100	15	260	110	4.8	1.4	14	100	7.4	120	25	2.9	2.1	6.3
G337.844−0.375	42	3.3	43	5	—	—	—	48	1.2	49	1.8	—	—	—
G337.927−0.458	860	140	880	210	—	—	—	680	62	830	120	3.4	2.7	12.3
G338.075+0.012	950	82	1400	170	9.3	2.6	82.2	790	55	1100	100	4.9	2.8	70.2
G338.383+0.163	66	9.2	98	20	10.1	3.2	54.3	44	3.2	63	7.1	6.2	2.6	39
G338.435+0.059	720	55	1000	120	7.4	5.4	2.7	470	38	850	100	7.8	4.8	8.4
G338.850+0.406	30	1.4	37	2.5	5.1	4.3	−1.4	22	1.6	30	3.2	4.9	4.1	−76.5
G338.922+0.624	240	6.3	260	9.6	3.1	1.5	−6.3	180	4.5	190	7	2.5	2	−50.2
G339.053−0.315	7.9	0.91	8.2	1.4	—	—	—	9	0.71	9.4	1	—	—	—
G339.477+0.185	83	4.2	89	6.5	—	—	—	75	2.7	79	3.9	—	—	—
G340.249−0.046	120	2.2	130	3.4	2.6	1.8	62.3	110	2.8	120	4.8	2.5	1.8	42
G340.249−0.372	230	3.8	230	5.6	2	0.7	28.3	210	5.3	220	8.4	2.2	1	40.9
G340.970−1.021	1.5	0.32	3.2	1.4	14.3	6.2	88.4	2.3	0.22	3.9	0.79	9.7	2.8	−83.2
G341.974+0.225	71	5.2	71	7.9	—	—	—	65	3.2	68	8.1	2.3	1.1	−76.1

Table 7.5 – continued from previous page

18GHz										24GHz				
Radio name	f_{peak} (mJy beam ⁻¹)	Δf_{peak} (mJy beam ⁻¹)	f_{int} (mJy)	Δf_{int} (mJy)	Major (arcsec)	Minor (arcsec)	PA (°)	f_{peak} (mJy beam ⁻¹)	Δf_{peak} (mJy beam ⁻¹)	f_{int} (mJy)	Δf_{int} (mJy)	Major (arcsec)	Minor (arcsec)	PA (°)
G343.353-0.067	76	2.8	130	8.5	8.1	7.3	58	46	3.4	100	13	7.7	7	46.9
G343.757-0.163	1.5	0.24	2.1	0.48	8.7	1.9	81	2.9	0.32	4.4	0.72	5.6	4.1	45.1
G343.929+0.125	59	2.3	62	3.5	2	1	-2.5	65	1.6	65	2.4	—	—	—
G344.426+0.046	970	69	1800	230	9.5	6.9	6.4	630	54	1400	220	8.2	6.3	26.6
G344.582-0.024	10	0.67	10	0.95	—	—	—	9.8	0.66	11	1	3	0.9	-81.6
G345.004-0.224	410	14	420	20	1.7	0.8	-48.4	420	21	430	31	1.5	0.7	-46.1
G345.198-0.030	6.7	0.41	6.7	0.61	—	—	—	6.3	0.5	7.8	0.91	1.5	—	—
G345.407-0.952	790	50	830	110	—	—	—	880	60	840	87	—	—	—
G345.411-0.952	640	21	910	71	9.6	2.4	-61.3	510	25	760	86	7	2.9	-66.9
G345.440+0.205	45	6.5	84	22	12.7	3.5	-34.8	30	4	57	13	8	4.4	-29.3
G345.488+0.315	2600	100	3300	180	5.3	3.7	19.7	2100	96	2900	190	4.7	3.1	33.4
G345.804+0.048	56	2.2	66	5.1	6.5	2.5	80.3	23	1.2	26	2.4	4.3	1.6	71
G346.039+0.049	3.2	0.26	5.6	0.65	10.2	5.8	43.4	2.3	0.14	4.3	0.41	8.9	4.6	66.9
346.480+0.132	5.7	0.4	6.8	0.88	6.8	3.3	-75.8	4.9	0.7	5	1.1	—	—	—
G346.522+0.083	310	19	610	56	10.8	8.1	30.3	210	15	420	46	9.3	6.6	72.8
G347.628+0.148	260	23	270	35	—	—	—	230	12	230	18	—	—	—
G347.871+0.014	290	10	330	17	4.2	0.9	14.9	220	8.9	230	14	—	—	—
G348.892-0.179	240	17	350	36	8.8	3.1	-24.5	190	18	300	42	8.1	2.7	-22.1
G350.011-1.342	7.4	0.41	8	0.64	2.9	1.9	56.2	8.7	0.46	9	0.69	—	—	—
G350.015+0.433	210	10	220	15	2.6	1.1	-63.3	190	8.7	200	13	—	—	—
G350.103+0.082	580	57	1500	250	12.6	10	-2.7	330	64	960	520	10.8	8.1	16.5
G350.180+0.014	130	12	210	62	7.5	7	-66.9	86	4.1	140	18	6.9	4.8	-71.3
G350.340+0.141	18	2.4	21	4.1	5.2	1.5	-47.3	15	1.4	18	2.5	4.4	2.3	-74
G350.343+0.116	30	0.68	38	3	5.1	4.6	4.1	20	0.78	21	2	—	—	—
G350.358-0.051	1.4	0.055	1.6	0.16	—	—	—	1.1	0.077	1.1	0.16	—	—	—
G351.245+0.667	1900	170	7900	1300	17.4	14.5	21.2	670	92	5000	1500	19.1	14.7	49.3
G351.383-0.181	1	0.19	1.5	0.42	7.7	2.9	25.1	1.2	0.23	1.9	0.66	—	—	—
G351.417+0.645	3000	86	3300	140	3.1	2.1	-51.1	2600	59	3000	100	3.1	2.2	-62

Table 7.5 – continued from previous page

Radio name	18GHz						24GHz							
	f_{peak} (mJy beam $^{-1}$)	Δf_{peak} (mJy beam $^{-1}$)	f_{int} (mJy)	Δf_{int} (mJy)	Major (arcsec)	Minor (arcsec)	PA ($^{\circ}$)	f_{peak} (mJy beam $^{-1}$)	Δf_{peak} (mJy beam $^{-1}$)	f_{int} (mJy)	Δf_{int} (mJy)	Major (arcsec)	Minor (arcsec)	PA ($^{\circ}$)
G351.581−0.353	970	91	980	130	—	—	—	980	44	980	63	3.1	—	—
G351.777−0.539	260	13	310	23	5.5	2.8	85.3	220	17	270	29	3.6	2.4	79.9
G352.132−0.945	1.9	0.2	2.1	0.34	—	—	—	2.5	0.22	2.6	0.33	—	—	—
G352.517−0.155	130	2.8	140	4.4	5.4	1.9	−75.1	140	2.1	140	3.2	2.6	0.5	−63.2
G352.623−1.076	1.2	0.2	1.3	0.39	—	—	—	1.7	0.17	2.8	0.49	7	5.2	64.1
G352.630−1.067	1.8	0.28	2.8	0.65	8.6	5.3	33.4	2.1	0.37	3.1	0.82	7.8	4.2	−78.2
G352.856−0.203	200	17	400	57	15.3	7.6	86.4	120	10	280	38	14.6	6.2	−86.9
G353.363−0.166	340	9.3	360	14	3.5	2.2	81.4	290	8.5	320	14	3.1	2.1	81.7
G353.387+0.431	46	3.2	77	7.7	8.1	7.9	−14.5	25	3	48	8.6	7.6	7.1	47.6
G353.410−0.360	610	81	810	190	—	—	—	490	61	540	100	—	—	—
G354.205−0.038	140	8.1	130	12	—	—	—	130	8.9	140	14	2.8	2.3	65.1
G354.724+0.300	490	20	540	31	3.6	2.7	75.8	470	15	520	24	3	1.8	54.5

TABLE 7.6: Spectral index and lower limit measurements for the high frequency radio detections that present 5-GHz radio emission. The average offset and size has been taken for sources that contain more than one 5-GHz radio counterpart and is represented with a †. The 5-GHz integrated flux upper limits are given as 3σ thresholds.

Radio name	f_{int} 5-GHz (mJy)	Δf_{int} 5-GHz (mJy)	Observed 5-GHz size (arcsec)	f_{peak} 24 GHz (mJy beam $^{-1}$)	Δf_{peak} 24 GHz (mJy beam $^{-1}$)	Offset (arcsec)	α	$\Delta\alpha$
G300.969+1.148	370	18		490	35	2.4	0.19	0.036
G301.136−0.225	300	11		1000	110	3.4	0.77	0.048
G302.033+0.626	< 0.56			0.84	0.07		>	
G305.886+0.017	< 0.46			1.3	0.1		>	
G308.056−0.396	110	0.25	2.6	190	8.7	0.39	0.38	0.019
G308.651−0.508	0.7	0.087	2.3	2.9	0.38	3.1	0.89	0.075
G309.384−0.135	< 0.35			2.5	0.24		>	
G309.920+0.479	350	1.8	2.8	880	49	2.6	0.59	0.023
G310.144+0.760	4.1	0.16	3	7	0.33	2.1	0.34	0.025
G311.642−0.380	200	0.47	2.7	260	6.1	1.9	0.19	0.0094
G312.307+0.661	26	0.17	2.9	39	0.63	0.66	0.24	0.0071
G318.049+0.086	6.1	0.35	2.7	4.6	0.82	4.1	−0.18	0.077
G320.233−0.284	320	1.5	3.3	340	3.5	1.4	0.034	0.0046
G326.448−0.748	4	0.16	2.5	9.1	0.8	0.77	0.52	0.04
G328.164+0.586	1.9	0.13	2.3	5.4	0.27	0.57	0.67	0.035
G328.236−0.548	13	4		36	2.4	1.2	0.64	0.13
G329.183−0.314	1.5	0.19	3.1	5.5	0.54	1.4	0.83	0.066
G329.272+0.115	1.7	0.18	2.7	13	1.8	3.3	1.3	0.07
G329.610+0.114	< 0.42			1.7	0.24		>	
G330.284+0.493	42	0.37	3.1	33	3.1	0.35	−0.14	0.038
G333.314+0.104	2.4	0.13	2.8	2.8	0.078	2.2	0.078	0.024
G333.387+0.032	4.6	0.12	2.5	6.4	0.49	1.5	0.21	0.033
G335.059−0.428	< 0.64			1.5	0.083		>	
G335.585−0.290	< 0.37			3.2	0.44		>	
G335.789+0.174	< 0.38			1.7	0.1		>	
G336.410−0.258	24	0.32	3.2	31	3.4	0.38	0.17	0.045
G336.823+0.028	85	0.49	3.2	90	10	0.67	0.033	0.046
G337.097−0.929	< 0.35			1.8	0.3		>	
G337.404−0.402	110	0.95	2.6	160	2.2	1.1	0.13	0.0068

Table 7.6 – continued from previous page

Radio name	f_{int} 5-GHz (mJy)	Δf_{int} 5-GHz (mJy)	Observed 5-GHz size (arcsec)	f_{peak} 24 GHz (mJy beam ⁻¹)	Δf_{peak} 24 GHz (mJy beam ⁻¹)	Offset (arcsec)	α	$\Delta\alpha$
G337.632−0.078	50	0.26	2.9	49	3.7	0.79	−0.018	0.031
G337.705−0.053	96	0.7	2.6	310	20	1.1	0.76	0.026
G337.844−0.375	13	0.17	2.4	48	1.2	0.33	0.85	0.012
G339.053−0.315	1.3	0.13	2.3	9	0.71	0.65	1.2	0.052
G339.282+0.136	1.6	0.12	2.2	5.1	0.7	0.53	0.74	0.065
G339.477+0.185	72	0.49	3	75	2.7	1.4	0.027	0.015
G340.249−0.372	97	1	3	210	5.3	1.4	0.5	0.011
G340.970−1.021	—	—	—	2.3	0.22	—	—	—
G343.757−0.163	0.39	—	—	2.9	0.32	—	—	—
G343.929+0.125	19	0.15	2.5	65	1.6	1.5	0.78	0.011
G344.582−0.024	9.5	0.18	2.7	9.8	0.66	1.5	0.02	0.029
G345.004−0.224	170	9.3	—	420	21	1.9	0.59	0.031
G345.198−0.030	5.9	0.13	2.5	6.3	0.5	0.45	0.046	0.034
G345.407−0.952	380	5.9	2.8	880	60	0.69	0.53	0.029
G346.480+0.132	2	0.12	2.5	4.9	0.7	1.6	0.56	0.064
G347.628+0.148	140	6.6	—	230	12	1.4	0.33	0.029
G350.011−1.342	—	—	—	8.7	0.46	—	—	—
G350.015+0.433	—	0.47	2.9	190	8.7	0.71	0.28	0.019
G350.340+0.141	8.9	0.01	—	15	1.4	2.9	0.31	0.039
G350.343+0.116	7.3	0.01	3.6	20	0.78	1	0.64	0.016
G351.383−0.181	0.11	—	—	1.2	0.23	—	—	—
G351.417+0.645	—	—	—	2600	59	—	—	—
G351.581−0.353	320	0.01	0.78	980	44	5	0.72	0.018
G352.132−0.945	—	—	—	2.5	0.22	—	—	—
G352.517−0.155	22	—	1.1	140	2.1	—	1.2	0.014

Table 7.6 – continued from previous page

Radio name	f_{int} 5-GHz (mJy)	Δf_{int} 5-GHz (mJy)	Observed 5-GHz size (arcsec)	f_{peak} 24 GHz (mJy beam ⁻¹)	Δf_{peak} 24 GHz (mJy beam ⁻¹)	Offset (arcsec)	α	$\Delta\alpha$
G352.623–1.076	–	–		1.7	0.17	>		
G352.630–1.067	–	–		2.1	0.37	>		
G352.856–0.203	150	0.01	4.1	120	10	3.8	–0.14	0.036
G353.363–0.166	310	0.01	2.5	290	8.5	>	–0.057	0.012
G353.410–0.360	180	0.01	2.1	490	61	0.8	0.62	0.051
G354.205–0.038	100	0.01	2.1	130	8.9	1.9	0.14	0.029
G354.724+0.300	250	0.01	3.1	470	15	2.2	0.39	0.013

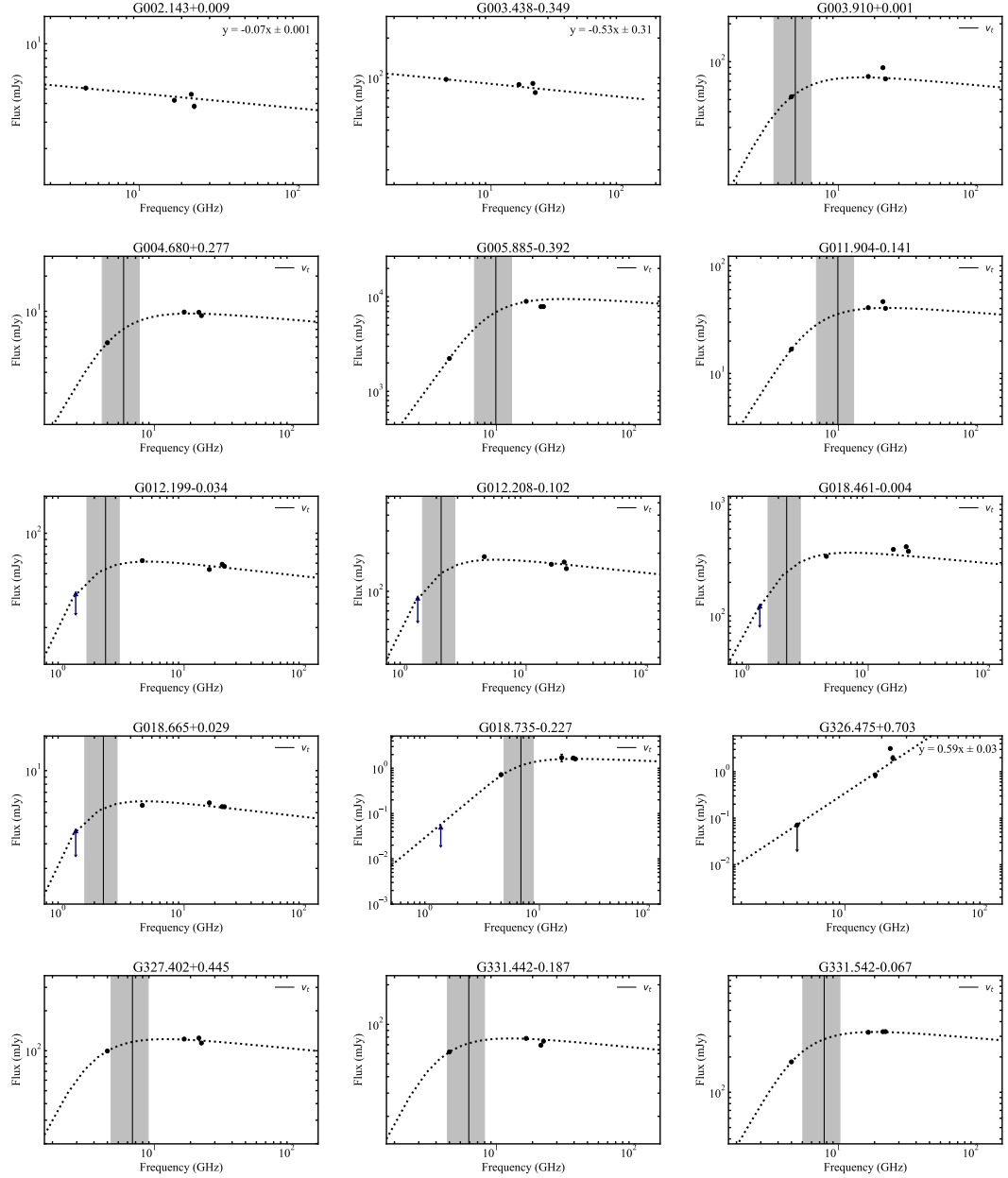


FIGURE 7.2: Radio SED fittings for the flux densities between 5 – 24 GHz. The solid vertical lines shows where the expected turnover frequency of the object lies. The grey shaded area represents the error associated with the turnover frequency

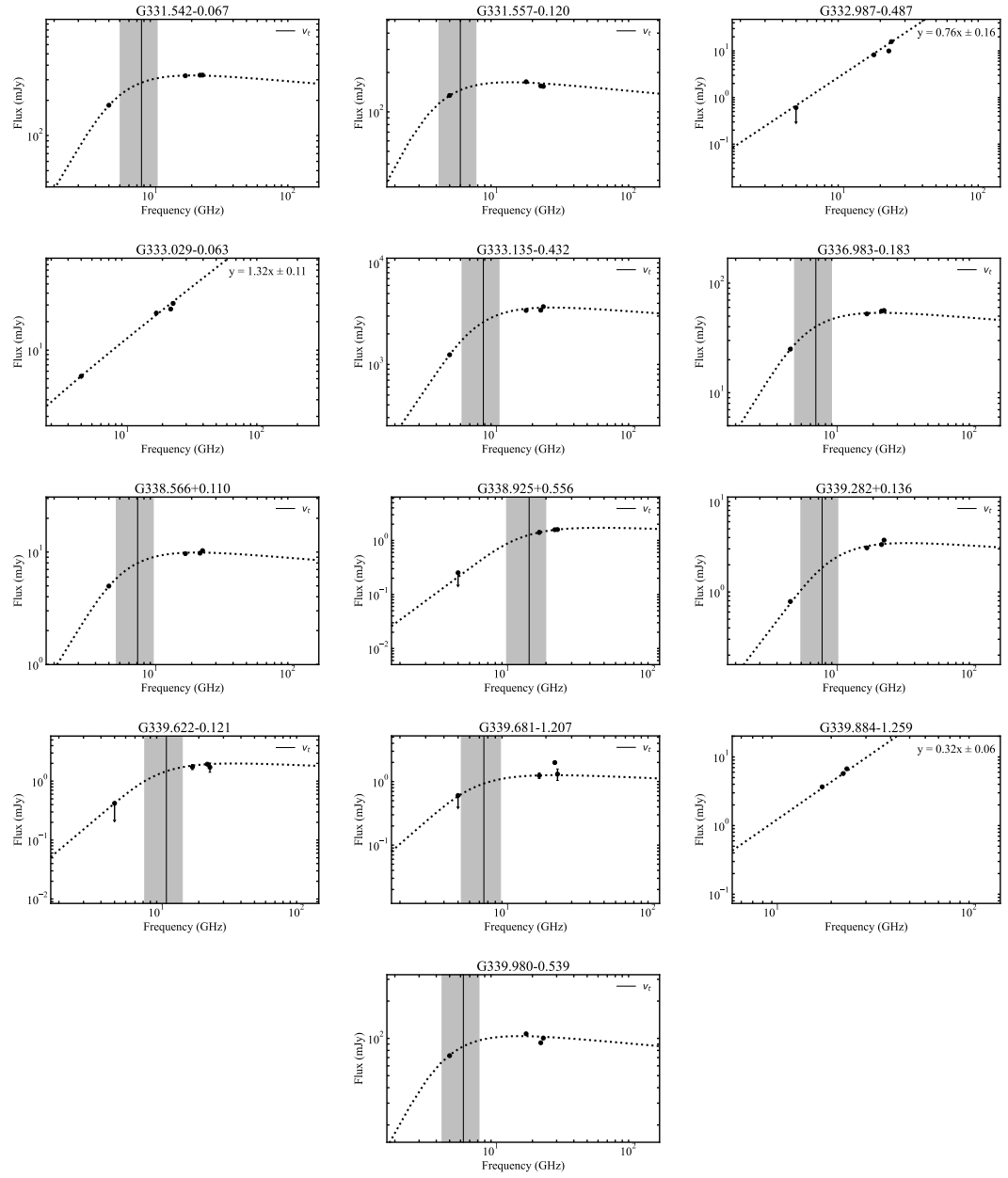


FIGURE 7.2: Cont.

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